Comparison of Geostudio and Plaxis in the Embankment dam Seepage and Slope Stability analysis: A case Study of Kundhi Dam, Oromia Ethiopia

Haimanot Shume Mosisa
A Thesis Submitted to the Department of Water Resources Engineering, College of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Water Resources Engineering (Hydraulic Engineering)

School of Postgraduate Studies Adama Science and Technology University

January, 2026
Adama, Ethiopia

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Mengistu Addis, PhD

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DECLARATION

I hereby declare that this thesis entitled "**Comparison of Geostudio and Plaxis in the Embankment dam Seepage and Slope Stability analysis: A case Study of Kundhi Dam, Oromia Ethiopia"** is my own work and has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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I, the major advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled **"Comparison of Geostudio and Plaxis in the Embankment dam Seepage and Slope Stability analysis: A case Study of Kundhi Dam, Oromia Ethiopia"** prepared under my guidance by **Haimanot Shume Mosisa** submitted in partial fulfillment of the requirements for the degree of Master of Science in **Water Resources Engineering (Hydraulic Engineering)**. Therefore, I recommend the submission of a revised version of the thesis to the department following the applicable procedures.

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I, the advisor of the thesis entitled **"Comparison of Geostudio and Plaxis in the Embankment dam Seepage and Slope Stability analysis: A case Study of Kundhi Dam, Oromia Ethiopia"** and developed by **Haimanot Shume Mosisa,** hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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We, the undersigned, members of the Board of Examiners of the thesis by **Haimanot Shume Mosisa** have read and evaluated the thesis entitled **"Comparison of Geostudio and Plaxis in the Embankment dam Seepage and Slope Stability analysis: A case Study of Kundhi Dam, Oromia Ethiopia"** examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirements of the degree of Master of Science in **Water Resources Engineering (Hydraulic Engineering)**.

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LIST OF ACRONYMS AND ABBREVATIONS

FE	Finite Element
FEM	Finite Element Method
FOS	Factor of Safety
FRL	Full Reservoir Level
GIS	Geographic Information System
GPS	Global Positioning System
ICOLD	International Commission on Large Dams
LE	Limit Equilibrium
MFL	Maximum Flood Level
MWL	Maximum Water Level
NPL	Normal Pool Level
PI	Plasticity Index
PLAXIS	Plastic Analysis of Structures (Finite Element Software)
RDD	Rapid Draw dawn
SEEP/W	Seepage and Water Flow Module in GeoStudio
SLOPE/W	Slope Stability Module in GeoStudio
UCS	Unconfined Compressive Strength
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
UTM	Universal Transverse Mercator
Qal	Quaternary Alluvium
Qel	Quaternary Eluvium

ABSTARCT

This study presents a comparative evaluation of seepage and slope stability analysis of the Finna Kundhi earthen dam located in Oromia Region, Ethiopia, recognizing that seepage and slope failure are major causes of embankment dam instability. The main objective of the study was to compare the performance of GeoStudio and PLAXIS software in simulating seepage behavior and slope stability under critical loading conditions. Two-dimensional numerical modeling was carried out using GeoStudio (SEEP/W and SLOPE/W) and PLAXIS based on finite element and limit equilibrium methods. Seepage and stability analyses were conducted under steadystate seepage at full supply level, end-of-construction, steady-state, and rapid drawdown conditions using available geotechnical and hydraulic data of the dam. The results showed that both software tools produced comparable seepage patterns, pore water pressure distributions, and factors of safety, with minor differences attributed to their numerical approaches. All computed factors of safety satisfied recommended international standards, indicating that the dam is stable under the considered conditions. The study recommends the use of GeoStudio for routine dam safety evaluation and PLAXIS for advanced stress–deformation analysis, together with continuous seepage monitoring to enhance long-term dam safety.

KEYWORDS: Embankment dam, Finna Kundhi Dam, GeoStudio, PLAXIS, Seepage and slope stability

1. INTRODUCTION

1.1. Background of the Study

Embankment dams are among the most commonly constructed dam types globally due to their adaptability to diverse site conditions and cost-effectiveness (ICOLD, 2021). These earth-filled structures primarily function to store water for irrigation, hydroelectric power generation, flood control, and municipal supply. However, the safety and durability of embankment dams critically depend on effective seepage control and slope stability, which significantly influence overall dam performance and failure risk (Zhang et al., 2023; Kumar & Singh, 2024).

Seepage through the dam body and foundation can induce internal erosion and piping, which are leading causes of embankment dam failures worldwide (Wang et al., 2022). Similarly, slope instability, particularly under static and dynamic loading conditions such as rapid reservoir drawdown or seismic events, threatens dam integrity and can precipitate catastrophic failure (Lee et al., 2023). Consequently, accurate prediction and analysis of seepage flow and slope stability are vital components of dam design, safety evaluation, and maintenance programs (Ahmed et al., 2024).

Numerical modeling has become an indispensable tool in geotechnical engineering for addressing the complex interactions involved in seepage and slope stability analyses. GeoStudio and PLAXIS are two leading software packages widely used in this domain. GeoStudio offers specialized modules such as SEEP/W for seepage and SLOPE/W for slope stability, employing flow net methods and limit equilibrium (Geo-Slope International, 2023). PLAXIS utilizes advanced finite element methods capable of simulating coupled hydro-mechanical behavior, nonlinear soil properties, and dynamic loading scenarios (Bentley Systems, 2024).

In Ethiopia, embankment dams like the Finna Kundhi Dam in the Oromia Region are critical for supporting agricultural development and water resource management. However, these dams often rest on heterogeneous soil formations with limited geotechnical data, complicating seepage and stability analyses (Tadesse et al., 2023). Although GeoStudio and PLAXIS have been applied individually in various Ethiopian dam projects, there remains a lack of comparative studies evaluating their performance under local geological and hydrological conditions (Gebremedhin & Alemu, 2024).

This gap is significant because differences in numerical approaches, soil constitutive models, and boundary condition settings can lead to variations in predicted seepage patterns, hydraulic gradients, and factors of safety (Lee et al., 2023; Ahmed et al., 2024). Understanding these discrepancies is crucial for selecting appropriate modeling tools, enhancing the accuracy of dam safety assessments, and developing effective risk mitigation strategies.

Therefore, this study evaluates the seepage and slope stability analysis capabilities of two geotechnical software tools, GeoStudio and PLAXIS, in relation to the Finna Kundhi Dam in Ethiopia. Given the importance of embankment dams for water resource management, the research will focus on understanding seepage behavior and slope stability to ensu re the dam's safety and performance. The study will conduct a comparative analysis of both software tools under various conditions, assessing their effectiveness in simulating seepage and predicting stability metrics such as factors of safety and potential failure modes.

The analysis aims to achieve two main objectives to evaluate GeoStudio's SEEP/W and SLOPE/W modules for their simulation capabilities, and to assess the performance of PLAXIS in similar contexts. By examining differences in hydraulic gradients, pore water pressures, and stability factors, the research will seek to highlight the strengths and weaknesses of each tool. The anticipated outcomes will include practical recommendations for engineers and regulatory bodies to enhance dam safety protocols and support informed decision-making in future geotechnical projects.

1.2 Statement of the Problem

The Finna Kundhi earthen dam, located in the Oromia Region of Ethiopia, is a key water infrastructure project developed to support irrigation and local water supply. As an embankment dam, its safety and long-term performance are strongly influenced by seepage behavior and slope stability. Due to its construction on variable foundation materials and exposure to fluctuating reservoir water levels during operation, the dam is potentially vulnerable to seepageinduced internal erosion and slope instability, which are recognized as the leading causes of embankment dam failures.

In practice, the safety evaluation of the Finna Kundhi Dam relies heavily on numerical modeling to estimate seepage quantities, pore water pressure distribution, and factors of safety under critical loading conditions such as end-of-construction, steady-state seepage, and rapid drawdown. However, differences in numerical approaches and modeling assumptions can significantly influence the predicted dam behavior, leading to uncertainty in stability assessment and decision-making.

GeoStudio and PLAXIS are the two most commonly applied geotechnical software tools for seepage and slope stability analysis in embankment dams. GeoStudio is widely used for routine dam safety assessments through seepage and limit equilibrium methods, whereas PLAXIS employs advanced finite element techniques capable of simulating coupled soil–water interaction and stress–deformation behavior. Despite their widespread use, these tools are based on different numerical formulations, constitutive soil models, and boundary condition implementations, which may result in varying predictions of seepage patterns, pore water ressures, and factors of safety.

For the Finna Kundhi Dam, such variations in modeling outcomes can directly affect the interpretation of dam safety and the reliability of engineering judgments. However, no systematic comparative evaluation has been conducted to assess the consistency and applicability of GeoStudio and PLAXIS for analyzing seepage and slope stability of the dam under local geological and operational conditions. This lack of comparative assessment represents a significant gap in dam safety evaluation practice.

Therefore, the need to reduce uncertainty in numerical modeling results and to enhance confidence in dam safety assessment provides the primary motivation for this study. By conducting a comparative analysis of seepage and slope stability of the Finna Kundhi earthen dam using GeoStudio and PLAXIS, this research aims to identify differences in predicted behavior and provide guidance for selecting appropriate numerical tools for embankment dam analysis under Ethiopian conditions.

1.3 Objective of the Study

1.3.1 General objective of the study

The general objective of the study is to a Comparison of Geostudio and Plaxis in the Embankment dam Seepage and Slope Stability analysis: A case Study of Kundhi Dam, Oromia Ethiopia.

Specific objective

- To conduct a comparative analysis of the seepage simulation capabilities of GeoStudio and PLAXIS for the Finna Kundhi Dam.
- To evaluate the accuracy of slope stability predictions generated by GeoStudio and PLAXIS under various static loading condition.
- To identify and compare the factors of safety calculated by both software tools and their implications for dam stability.
- To provide practical recommendations to engineers and regulatory bodies based on the findings of the comparative analysis, aimed at enhancing dam safety protocols and design methodologies.

1.4 Research Questions

- How does the prediction of seepage flow differ between GeoStudio and PLAXIS when applied to the Finna Kundhi Dam?
- What are the variations in hydraulic gradients and pore water pressures as computed by GeoStudio and PLAXIS for the embankment dam?
- What are the differences in slope stability factors of safety calculated by GeoStudio and
- PLAXIS under various loading conditions (e.g., static, seismic) for the Finna Kundhi Dam?
- How do the two modeling approaches (GeoStudio and PLAXIS) compare in predicting failure modes and potential landslide scenarios for the embankment dam?

1.5 Significance of the Study

This study is highly significant to the engineering and geotechnical fields, particularly in the areas of dam design, safety evaluation, and maintenance, with a specific focus on the Finna Kundhi earthen dam. By conducting a comparative analysis of GeoStudio and PLAXIS, the research offers valuable insights into the advantages and limitations of these widely used software tools for simulating seepage and slope stability. This knowledge helps engineers choose the most suitable modeling techniques for precise dam safety assessments. Moreover, the study improves dam safety evaluations by identifying critical seepage pathways and potential slope failure mechanisms, which are essential for preventing dam failures and ensuring safe operation. The comparison of factors of safety generated by both software further aids informed decision-making, allowing stakeholders to develop effective risk management and maintenance strategies based on dependable data. Additionally, the findings directly support the sustainable management of the Finna Kundhi dam, which is crucial for local water resource management, agriculture, and the livelihoods of nearby communities. Beyond its practical benefits, this research contributes to the academic field of geotechnical engineering and serves as a valuable resource for future studies and practical applications involving earthen dam analysis.

1.6 Scope of the Study

This study is specifically centered on the Finna Kundhi earthen dam, focusing on the analysis of seepage and slope stability using two well-established geotechnical software tools: GeoStudio and PLAXIS. The research includes seepage simulations that model groundwater flow and hydraulic gradients, alongside slope stability assessments under various static and dynamic loading conditions. A primary objective is to comparatively evaluate the modeling capabilities, accuracy, and outcomes-especially the factors of safety-produced by both GeoStudio and PLAXIS. However, the study excludes other critical aspects such as sedimentation processes, the structural design of dam components, and long-term environmental impacts. It also relies on the availability of accurate geotechnical and hydrological data specific to the Finna Kundhi dam site. The scope is geographically and temporally confined to the dam's current condition, without extending to future considerations like climate change impacts or extreme event predictions.

2. LITERATURE REVIEW

2.1. Embankment Dam

Embankment dams are among the most widely constructed hydraulic structures globally, with thousands exceeding 15 meters in height. China currently leads in embankment dam development, reflecting its extensive investments in water resource infrastructure (USSD, 2011). Despite advancements in engineering practices, many design aspects still rely heavily on empirical knowledge and professional judgment, underscoring the need for robust mathematical and numerical approaches to address complex geotechnical challenges. A realistic design for an embankment dam demands thorough investigation of foundation conditions and construction materials, coupled with controlled construction techniques to achieve specified compaction levels and moisture content (Fell et al., 2020). These measures are critical to ensuring long-term stability and minimizing risks such as internal erosion or differential settlement.

The popularity of embankment dams stems from their adaptability and cost-effectiveness. They utilize locally available materials, reducing transportation costs and environmental impact, and are suitable for diverse topographies, from wide valleys to steep-sided gorges (ICOLD, 2021). Their design flexibility allows for zoning with different fill materials, such as earth fill and rockfill, to optimize stability and seepage control. Properly designed embankments can accommodate settlement deformation without significant cracking, mitigating failure risks (Zhang et al., 2023). Additionally, they are compatible with a variety of foundation conditions, often making them the most economical choice compared to concrete alternatives (Kumar & Singh, 2024).

Embankment dams are classified based on material composition: earth fill dams consist of over 50% compacted soils, while rockfill dams predominantly use coarse-grained frictional materials. This classification guides material selection based on site-specific availability and geotechnical requirements (Briaud, 2022). For instance, rockfill dams are preferred in regions with abundant granular materials, whereas earth fill dams are constructed where cohesive soils dominate.

As vital infrastructure for water storage, flood mitigation, and hydropower generation, embankment dams require meticulous attention to stability, seepage control, and environmental sustainability. Recent advances in numerical modeling, such as finite element analysis and machine learning, have enhanced the ability to predict seepage patterns and slope stability under dynamic loading conditions (Wang et al., 2023). Sustainable practices, including the use of recycled materials and eco-friendly construction techniques, are also gaining traction to reduce the ecological footprint of dam projects (Ahmed et al., 2024). These innovations, combined with rigorous monitoring and maintenance protocols, ensure that embankment dams remain safe, resilient, and integral to global water resource management strategies.

2.1.1. Earth Fill Dams

Earth fill dams are gravity structures that resist sliding and overturning primarily through their self-weight (Craig, 2004). They are among the most common dam types globally, historically used for water diversion and flood protection, and later developed for reservoir storage. For smaller-scale applications, earth fill dams offer distinct technical and economic advantages, including the widespread availability of construction materials, relatively simple design principles, and reduced foundation preparation requirements compared to concrete structures (ICOLD, 2022). Their inherent flexibility also makes them suitable for areas with seismic activity.

However, earth fill dams possess certain disadvantages relative to other dam types. They are generally more susceptible to internal erosion, surface slides, and overtopping failure if not properly designed and maintained (Fell et al., 2014). Inadequate compaction during construction can lead to excessive seepage, while long-term performance requires continuous monitoring to manage slope erosion, control vegetation, and detect any abnormal seepage patterns. The basic typology of earth dams includes homogeneous embankments, zoned embankments with distinct core and shell materials, and diaphragm embankments featuring a narrow impervious wall.

2.1.2. Rock Fill Dam

Rock fill dams share characteristics with both gravity and earth fill dams. Modern practice employs well-graded, intensively compacted rock fill, which has largely replaced the older dumped rock-fill methods. The use of heavy compaction equipment is critical, as the compacted density directly governs the shear strength and post-construction settlement of the fill (Novak et al., 2018).

The primary advantages of compacted rock fill are its high frictional shear strength, which permits steeper embankment slopes than earth fill, and its high permeability, which mitigates pore-water pressure issues during construction and operation. Key disadvantages include challenges in controlling the gradation of quarried or excavated rock and the potential for significant, and sometimes differential, settlement. This settlement can create interface problems, particularly where rigid rock fill shoulders abut a more compressible central core. Contemporary understanding of rock fill quality, large-scale testing methods, and the non-linear shear strength envelope of the material is detailed in modern references (ICOLD, 2018; Soroush & Aghaei Araei, 2019).

2.2. Dam Type Selection

The selection of an appropriate dam type is a pivotal decision in the planning and design of water resource projects. This decision hinges on a multitude of interrelated factors, including site-specific conditions, the intended purpose of the dam, availability of construction materials, project cost, and environmental and social considerations. A comprehensive understanding of these factors is essential to optimize dam performance, safety, and sustainability.

Site conditions play a fundamental role in determining the most suitable dam type. The topography of the proposed dam site, particularly the shape and slope of the valley, influences design choices significantly. Narrow, steep-sided valleys often favor arch dams due to their ability to transfer water pressure efficiently to the abutments, while wide valleys are more amenable to embankment or gravity dams that rely on their mass for stability (ICOLD, 2021). Geological characteristics of the foundation, such as strength, permeability, and stability, are equally critical. Strong, competent rock foundations are ideal for concrete dams, including gravity and arch types, whereas weaker or more permeable soils may necessitate embankment dams that can better accommodate foundation variability (Fell et al., 2020). Additionally, seismicity must be considered, as dams located in earthquake-prone regions require designs capable of withstanding dynamic loads to prevent catastrophic failure (Wang et al., 2023).

The intended purpose of the dam further guides type selection. For water storage and irrigation, embankment and gravity dams are commonly employed due to their adaptability and costeffectiveness. Hydropower projects, especially those involving high hydraulic heads, often prefer concrete dams-gravity, arch, or buttress-because of their structural robustness and ability to handle high stresses (Zhang et al., 2023). Flood control dams typically utilize embankment designs equipped with large spillways to safely manage excess flows. Thus, the functional requirements of the project shape the engineering and economic considerations in dam type choice.

Material availability at or near the construction site significantly influences economic feasibility and design decisions. Embankment dams' benefit from the use of locally sourced earth and rock materials, minimizing transportation costs and environmental impacts (Kumar & Singh, 2024). Conversely, if cement, aggregates, and other components are readily accessible, concrete dams may be preferred despite their generally higher initial costs and longer construction times. This trade-off between material availability and construction logistics is a recurring theme in dam engineering.

Cost and construction time are practical considerations that often weigh heavily in decisionmaking. Embankment dams are generally less expensive and faster to build, especially in remote or logistically challenging locations, making them attractive for many developing regions (Ahmed et al., 2024). Concrete dams, while more costly and time-consuming, offer longer service lives and higher structural stability, which may justify the investment for large-scale or high-risk projects.

Environmental and social factors have become increasingly prominent in dam type selection. The ecological impacts of dam construction and operation-including effects on aquatic ecosystems, sediment transport, and water quality-must be carefully assessed to minimize adverse outcomes (ICOLD, 2021). Moreover, the potential displacement of communities or the disturbance of cultural heritage sites can influence the choice of dam type and site layout, necessitating thorough social impact assessments and stakeholder engagement.

Common dam types include embankment dams, which are further classified as earth fill or rockfill depending on the predominant fill material. Earthfall dams are constructed primarily from compacted soils such as clay, silt, sand, and gravel, making them suitable for wide valleys and softer foundations. Rockfill dams utilize coarse-grained, frictional materials like large rocks and boulders, often combined with impermeable membranes to control seepage, and are ideal where abundant rock material is available (Briaud, 2022). Concrete dams encompass gravity dams, which resist water pressure through their own weight; arch dams, which transfer loads to abutments via their curved shape; and buttress dams, which employ reinforced concrete supports to reduce material usage (Fell et al., 2020). Composite dams, combining embankment and concrete sections, offer design flexibility tailored to specific site conditions, while barrages serve as low-head structures primarily used for flow regulation in irrigation schemes.

The decision-making process for dam type selection involves detailed site investigations, including topographic, geological, and hydrological surveys, to characterize the physical environment accurately. Feasibility studies evaluate the suitability of various dam types against technical, economic, and environmental criteria. Design optimization through engineering analyses and numerical modeling refines the selected option to meet safety and performance standards. Environmental and social impact assessments ensure that potential negative effects are identified and mitigated, while stakeholder consultations facilitate inclusive decisionmaking and community acceptance (Ahmed et al., 2024).

Despite advances in technology and methodology, challenges persist in dam type selection. Uncertainties in site data, such as incomplete geological information or hydrological variability, can lead to suboptimal choices with long-term consequences. Climate change introduces additional complexity by altering rainfall patterns and increasing the frequency of extreme weather events, necessitating adaptive and resilient dam designs (Wang et al., 2023). Furthermore, balancing competing priorities-cost, environmental protection, structural performance, and social acceptance-requires careful trade-offs and multidisciplinary collaboration.

Dam type selection is a multifaceted process that demands a holistic approach integrating sitespecific conditions, project objectives, material logistics, economic considerations, and environmental and social factors. By following systematic evaluation procedures and leveraging contemporary engineering tools, planners and engineers can identify the most appropriate dam type to ensure the success, safety, and sustainability of water resource projects.

2.3. Earthen Dam Safety Issues and Failure Causes

Dam safety is a critical aspect of water resource management, as failures can lead to devastating consequences including loss of life, environmental damage, and economic disruption. To prevent such disasters, rigorous safety inspections and thorough analyses of failure mechanisms are indispensable. Understanding the unique characteristics of each dam, including its structural components and site-specific conditions, is fundamental to effective risk mitigation (Ahmed et al., 2024; Wang et al., 2023). In the design of embankment dams, multiple factors must be carefully considered, such as water retention capacity, seepage behavior, slope stability of both the dam and reservoir, abutment integrity, and foundation treatment techniques (Lee et al., 2023). The selection and utilization of locally available materials are essential to optimize the design and ensure compatibility with the natural conditions of the site, which significantly influence the dam's performance and longevity (Kumar & Singh, 2024). Recent studies have highlighted that neglecting detailed assessments of foundation conditions and construction materials can compromise the structural safety and operational efficiency of earth dams (Zhang et al., 2023). Therefore, modern embankment dam design increasingly integrates advanced geotechnical investigations and numerical modeling to address these complexities, ensuring resilient and sustainable infrastructure in the face of evolving environmental challenges (Ahmed et al., 2024; Wang et al., 2023).

2.4. Earthen Dam Seepage and Failure Modes

Earth dam failures can result from several factors including seepage piping, foundation instability, material degradation, deformation, and seismic events. Among these, seepage-related problems remain the predominant cause of failures globally, often leading to internal erosion and piping that compromise dam integrity (Zhang et al., 2023; Ahmed et al., 2024). To mitigate such risks, comprehensive inspections and continuous monitoring both during and after construction are essential. During construction, field measurements of pore water pressures and deformation provide critical data for assessing dam behavior under loading conditions. Postconstruction monitoring typically focuses on seepage rates and piezometric head levels to detect early signs of distress (Wang et al., 2023; Lee et al., 2023). Without diligent observation and timely intervention, earth dams may fail abruptly, releasing large volumes of water with potentially catastrophic consequences for downstream communities and infrastructure (Kumar & Singh, 2024). Recent studies emphasize that systematic seepage monitoring is a key component of dam safety management, enabling early detection of piping and seepage anomalies that could otherwise lead to failure (Ahmed et al., 2024; Zhang et al., 2023). Therefore, integrating advanced sensor technologies and real-time data analysis into dam monitoring programs is increasingly recognized as vital for enhancing the resilience and safety of earth dams in the face of evolving environmental and operational challenges.

2.4.1 Effects of Uncontrolled Seepage on Embankment Dams

Uncontrolled seepage is consistently identified in the literature as one of the dominant causes of embankment dam distress and failure worldwide. According to ICOLD (2018) and Fell et al. (2015), seepage through the dam body, foundation, or abutments alters pore water pressure distributions, reduces effective stress, and may initiate internal erosion mechanisms such as piping. Statistical reviews of historical dam failures indicate that seepage-related mechanisms account for more than one-third of embankment dam failures globally, emphasizing the critical importance of seepage control in dam design and operation (ICOLD, 2018).

Elevated pore water pressures generated by seepage reduce the shear strength of embankment materials by lowering effective stress, thereby increasing the likelihood of slope instability, particularly on the downstream face under steady-state reservoir conditions (USACE, 2003). Studies by Foster et al. (2000) demonstrate that high hydraulic gradients near the downstream exit can mobilize fine soil particles, leading to progressive internal erosion and eventual piping failure if not adequately controlled. Uncontrolled seepage may also result in excessive saturation of downstream zones, causing softening of materials, differential settlement, and cracking, which further concentrate seepage paths and accelerate deterioration (Terzaghi et al., 1996).

Observed indicators of seepage-related distress include increased seepage discharge, turbid flow at drainage outlets, wet spots on downstream slopes, and abnormal piezometric readings (USBR, 2014). If such warning signs are not addressed through timely remedial measures, seepage may progress to complete structural failure. Consequently, modern embankment dam design emphasizes the incorporation of impervious cores, cutoff trenches, properly graded filters, and drainage systems to control seepage quantities and hydraulic gradients (ICOLD, 2018; Fell et al., 2015).

2.4.2 Seepage Analysis Through Embankment Dams

Seepage analysis is a fundamental component of embankment dam safety evaluation, as it provides quantitative insight into groundwater flow patterns, pore water pressure distributions, and hydraulic gradients within the dam and its foundation. Classical seepage theory is based on Darcy's law, which governs laminar flow through porous media. However, analytical solutions are limited to simple geometries and homogeneous soil conditions and are therefore insufficient for complex embankment dams with zoned materials and heterogeneous foundations (Cedergren, 1997).

To overcome these limitations, numerical methods—particularly finite element methods—are widely applied in contemporary dam engineering. Software packages such as SEEP/W solve the governing seepage equations under steady-state and transient conditions, enabling accurate prediction of phreatic surfaces, seepage fluxes, and pore water pressures (Geo-Slope International, 2023). Several studies have shown that seepage behavior is highly sensitive to material permeability, zoning configuration, and reservoir operating conditions (Zhang et al., 2021; Wang et al., 2022).

Steady-state seepage at full supply level is generally considered a critical design condition for downstream slope stability due to sustained high pore water pressures (USACE, 2003). Transient seepage analysis, particularly during rapid drawdown, is equally important, as pore pressures dissipate more slowly than reservoir water levels, leading to temporary but critical reductions in stability (Duncan et al., 2014). Validation of numerical seepage models using field instrumentation data, such as piezometer readings, is widely recommended to improve model reliability and confidence in predicted results (USBR, 2014).

2.4.3 Estimation of Seepage

The estimation of seepage quantity is essential for assessing the hydraulic performance and safety of embankment dams. Seepage estimates are used to evaluate the adequacy of drainage systems, assess potential internal erosion risks, and identify abnormal flow conditions during dam operation (ICOLD, 2018). Traditional flow-net methods provide approximate seepage estimates but are limited by assumptions of homogeneity and simplified boundary conditions (Cedergren, 1997).

Modern engineering practice relies primarily on numerical modeling techniques to estimate seepage quantities. Finite element–based analyses compute seepage discharge by integrating flow rates across specified sections of the dam or foundation, allowing for anisotropic permeability, layered soil profiles, and complex geometries (Geo-Slope International, 2023). Research indicates that seepage quantity increases with reservoir head and foundation permeability, while effective drainage systems significantly reduce pore water pressures and seepage-induced risks (Fell et al., 2015).

Recent studies also emphasize the importance of sensitivity and uncertainty analysis in seepage estimation, as soil hydraulic properties are inherently variable (Wang et al., 2022). Accurate seepage estimation therefore forms a critical basis for evaluating piping potential and ensuring compliance with international dam safety standards.

2.5 Modes of Slope Failure and Stability Analysis

Slope instability is one of the principal failure modes of embankment dams and is closely linked to seepage behavior and pore water pressure conditions. Slope failure occurs when driving forces exceed the available shear resistance along a potential slip surface. Common failure modes include circular (rotational) failures in homogeneous embankments and composite or non-circular failures in zoned embankments or dams founded on layered soils (Duncan & Wright, 2005).

Downstream slope failures are typically associated with prolonged steady-state seepage conditions, whereas upstream slope failures are commonly triggered by rapid reservoir drawdown, which removes stabilizing hydrostatic pressure while excess pore water pressures remain within the embankment (USACE, 2003). Elevated pore water pressures reduce effective stress and shear strength, thereby controlling slope stability behavior under most loading conditions.

Slope stability analysis is commonly performed using limit equilibrium methods or finite element methods. Limit equilibrium approaches, such as those implemented in SLOPE/W, compute a factor of safety by comparing resisting and driving forces along assumed slip surfaces. Finite element methods, as used in PLAXIS, provide a more advanced representation of stress–strain behavior and soil–water interaction, allowing simulation of deformation and progressive failure mechanisms (Brinkgreve et al., 2018). International guidelines generally recommend minimum factors of safety ranging from 1.3 to 1.5 for static loading conditions, depending on dam importance and loading scenario (ICOLD, 2018).

2.6 Comparison with Other Studies

Several previous studies have compared the application of GeoStudio and PLAXIS in seepage and slope stability analysis of embankment dams. Research by Nourani and Fatehi (2011) and Zhang et al. (2021) reported that both software tools produce similar seepage patterns and pore water pressure distributions, although quantitative differences arise due to variations in numerical formulation and soil constitutive models. Limit equilibrium–based analyses generally yield slightly higher factors of safety compared to finite element–based strength reduction methods (Duncan et al., 2014).

Comparative studies conducted by Lee et al. (2020) and Ahmed et al. (2023) showed that PLAXIS often predicts lower factors of safety because it accounts for stress redistribution, material nonlinearity, and deformation compatibility. GeoStudio, however, is widely favored for routine dam safety evaluation due to its computational efficiency and direct implementation of regulatory design criteria. These studies emphasize that discrepancies between results should be interpreted in light of modeling assumptions rather than treated as inconsistencies.

Overall, the literature recommends a complementary use of GeoStudio for preliminary and regulatory assessments and PLAXIS for detailed stress–deformation analysis. This approach enhances confidence in embankment dam safety evaluation and supports informed engineering decision-making.

3. MATERIALS AND METHODS

3.1. Description of the Study Area

3.1.1. Location

The project area is found in Borena Zone of the Oromia National Regional State. It is located in Ele Waye district at Golba kebele. The geographic coordinate location of the headwork site is at UTM zone 37 367680 mE and 536831mN. It is found at a distance of about 573 km to the South direction from Finfinnee. It is located at about 30km distance from the district capital Ele Waye through all-weather road. To reach the headwork site from the existing road, the project requires 3km new access road Overall location the project site has been shown on Figure 3.1 below. Catchment area at the dam site: 210.26 km2, Reservoir Area @ MWL:108.72_ha, Full Reservoir Capacity @ FRL: 13. 35Mm3.Finna Kundhi project has been underway with the objective of implementing 842ha irrigation development. Kundhi Dam to be Zone earthen fill dam instead of other type of dam.

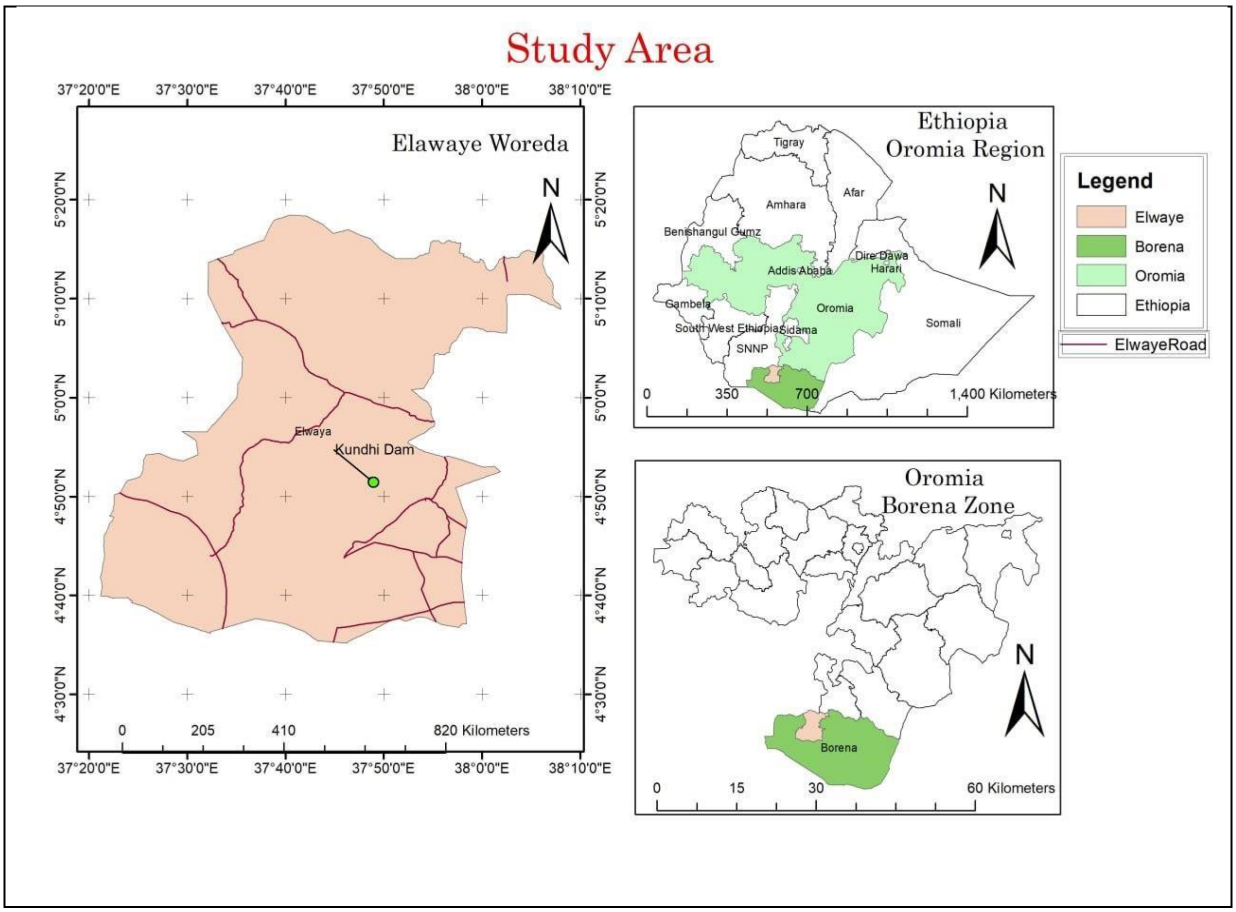


Figure 3-1: Location map of the project area (watershed) and proposed dam site

3.1.2 Topography

The Finna Kundhi Dam site is located in gently undulating to moderately rolling terrain typical of the Borena Zone lowlands. Elevation gradually decreases toward the Kundhi River, with the dam axis situated at an average elevation of about 1,109 m above mean sea level. Surface runoff from the catchment drains naturally toward the river channel, creating favorable conditions for reservoir formation. However, localized slopes and sparsely vegetated areas are susceptible to erosion during high-intensity rainfall events, necessitating appropriate erosion control measures.

3.1.3 Climate

The study area experiences a semi-arid to arid climate characterized by low and variable rainfall, high temperatures, and high evapotranspiration. Rainfall follows a bimodal pattern, with main rains from March to May and secondary rains from September to November. Mean annual rainfall ranges from approximately 600 to 800 mm. Average annual temperatures vary between 22°C and 25°C, with maximum daily temperatures frequently exceeding 30°C. Prevailing wind conditions were considered in estimating wave action and determining reservoir freeboard.

3.1.4 Geology

The geological formation at the Finna Kundhi Dam site consists mainly of Cenozoic volcanic rocks underlain by Precambrian crystalline basement formations. The dam foundation is predominantly composed of Bulal Basalt, which exhibits competent engineering properties with moderate weathering. Quaternary alluvial and eluvial deposits, composed of sand, silt, clay, and gravel, overlie the bedrock along the river channel, with thicknesses reaching up to about 5 m. These materials significantly influence seepage behavior and foundation stability and wercarefully evaluated during dam design.

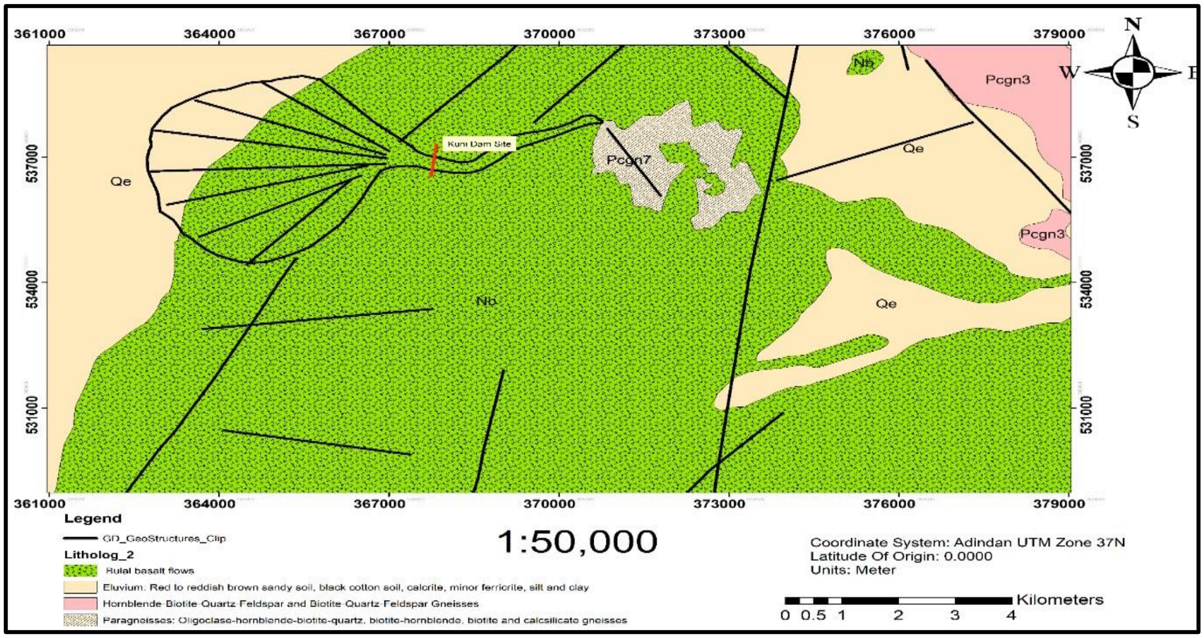


Figure 3-2: Geological Map of the project area and its surroundings, after Geological Map of Yabello

3.2. Data Collection

Data collection for this study was carried out in two main phases: primary data collection and secondary data collection. The primary data were obtained through direct field investigations at the Finna Kundhi Dam site, while the secondary data were gathered from existing project documents, technical reports, and geotechnical databases.

3.2.1. Primary Data Collection

Primary data were collected from the site. These data include topographic survey of the headwork axis, physical observation of the site condition and gathering of necessary photograph and other relevant information.

Table 3-1: Primary data

Primary Data			
Specific Data Collected	**Source**	**Method of Collection**	**Purpose in the Study**
Topographic data of dam axis and reservoir area	Field survey at Finna Kundhi Dam site	GPS survey and direct field measurement	Development of dam geometry and numerical model input
Site condition and visual inspection data	Finna Kundhi Dam site	Field observation and photography	Verification of dam condition and seepage indicators
Groundwater level and pore water pressure	Installed piezometers at dam site	Piezometer readings (Casagrande and vibrating wire piezometers)	Validation of seepage analysis and pore pressure distribution
Dam instrumentation layout	Design drawings and field verification	On-site inspection	Calibration and interpretation of seepage behavior

3.2.2. Secondary Data Collection

comprised a comprehensive review of existing project documentation, including feasibility studies, design reports, geological maps, and laboratory test results.

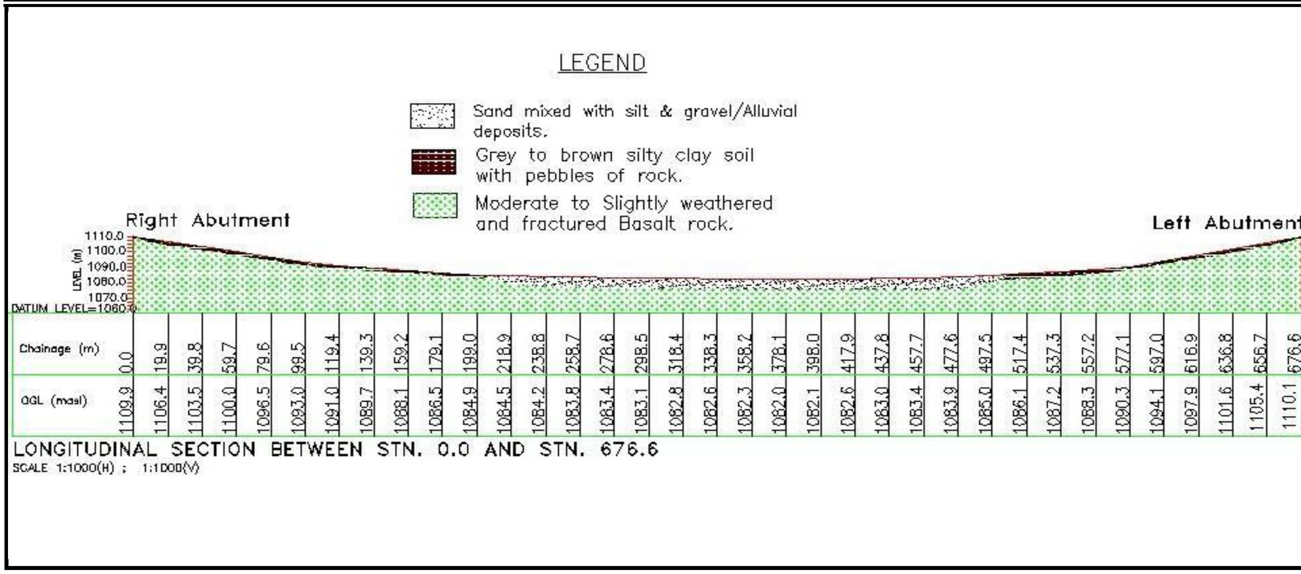
Table 3-2: Secondary data

Secondary Data			
Specific Data Collected	**Source**	**Method of Collection**	**Purpose in the Study**
Geological and geotechnical investigation reports	Oromia Irrigation and Pastoralist Development Bureau	Review of project documents	Determination of foundation conditions and soil layering
Soil laboratory test results (c, φ, γ, PI, k)	Engineering Corporation of Oromia (Project Reports)	Document review	Input parameters for seepage and slope stability modeling
Dam design drawings and specifications	Finna Kundhi Dam Project Office	Review of approved design documents	Definition of dam geometry and zoning
Reservoir water levels (FSL, MWL, RDD conditions)	Project feasibility and design reports	Document review	Simulation of critical loading conditions
Previous studies, guidelines, and standards	ICOLD, USACE, USBR publications	Literature review	Benchmarking factor of safety and analysis criteria
Software manuals and theoretical background	GeoStudio and PLAXIS documentation	Technical literature review	Model setup and result interpretation

The Kundhi Dam is designed as a zoned embankment dam with a central clay core. The construction materials required include rock fill and shell material for structural support,

Table 3-3: Construction material engineering property

Construction Material Type	**Property**							
Material Type	**Hydraulic Conductivity (K), cm/s**	**Cohesion (c) MPa**	**Internal Friction Angle Ø (Degree)**	**Unit Weight (Ɣ) kN/m³**	**Water Absorption (%)**	**Plasticity Index (PI)**	**UCS, MPa**	**Distance (km)**
Rock Fill	10^{-2}	4.3	31.9	22	1	NP	80	1–3
Shell Material	10^{-2}	1.59	26.11	21	2	NP	12.5	1–3
Filter Material (Sand)	10^{-2}–10^{-4}	0	35	16	–	0	–	42
Clay Core (elluvial)	10^{-4}–10^{-6}	0.15	20	20	–	25	0.05	4



Piezometer Readings: Take piezometer reading. Regular readings will help in understanding groundwater levels and seepage conditions. Additionally, installation of dam instrumentation (Vibrating Wire piezometer) which used measure to pore water pressure were carried out jointly.

Figure 3-3: Natural groundwater can be observed /measured and a groundwater velocity and direction obtained.

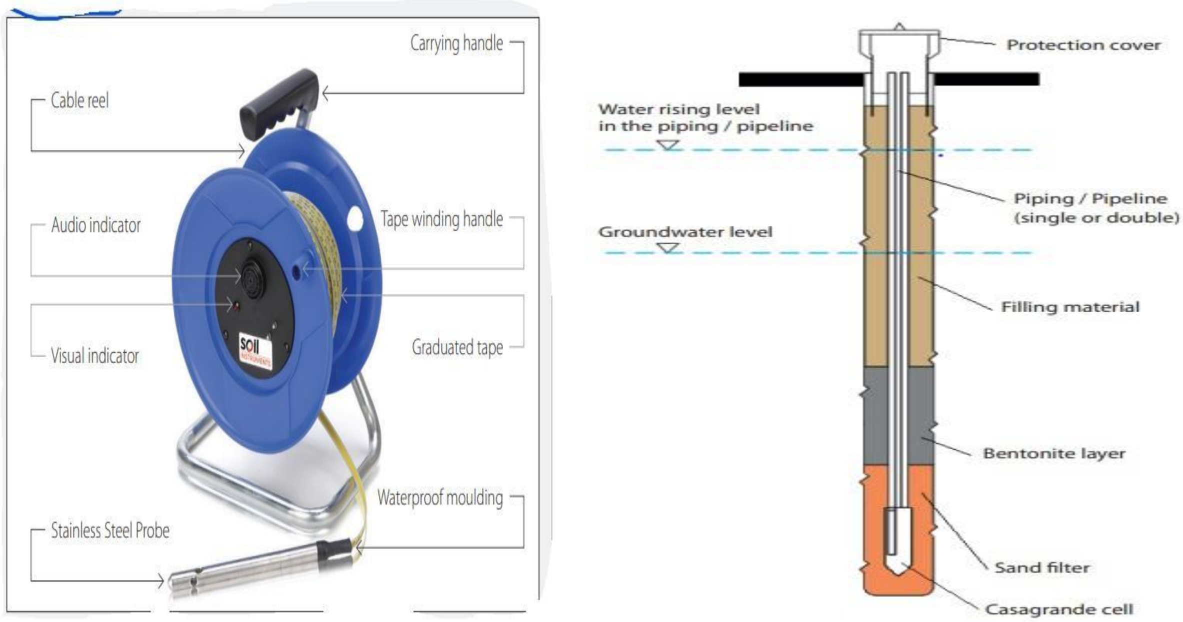
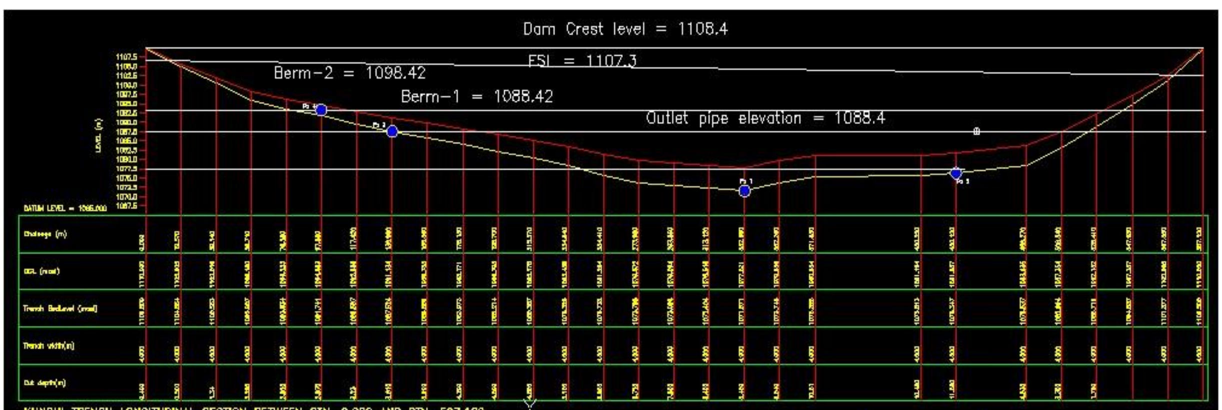


Figure 3-4: The installation location of the instrument

Note: The installation location of the instrument, vibrating wire Piezometer will be as shown in the figures below which are taken from the design drawings provided by the engineer.



Piezometer lists	Section	Chainage	Location	Elevation	Remark
Pz 1	Section 1-1	@+332.690	Dam center	1071.571 - 1077.821	Response Zone
				1077.821 - 1078.821	Bentonite sealed
				1078.821 - 1108.4	gravel backfill
Pz 2	Section 2-2	(@+450)	Dam center	1077.5 - 1085.5	Response Zone
				1085.5 - 1086.5	Bentonite sealed
				11086.5 - 1108.4	Gravel backfill
Pz 3	Section 3-3	(@+136.991)	Dam center	1087.524 - 1095.0	Response Zone
				1095.0-1096.0	Bentonite sealed
				1096.0 - 1108.4	gravel backfill
PZ 4	Section 4-4	(@+97.85)	Dam center	1091.741 - 1107.3	Response Zone
				1107.3 - 1108.4	Bentonite Sealed

Figure 3-5: Installation diagram of vibrating wire piezometers with chain ages

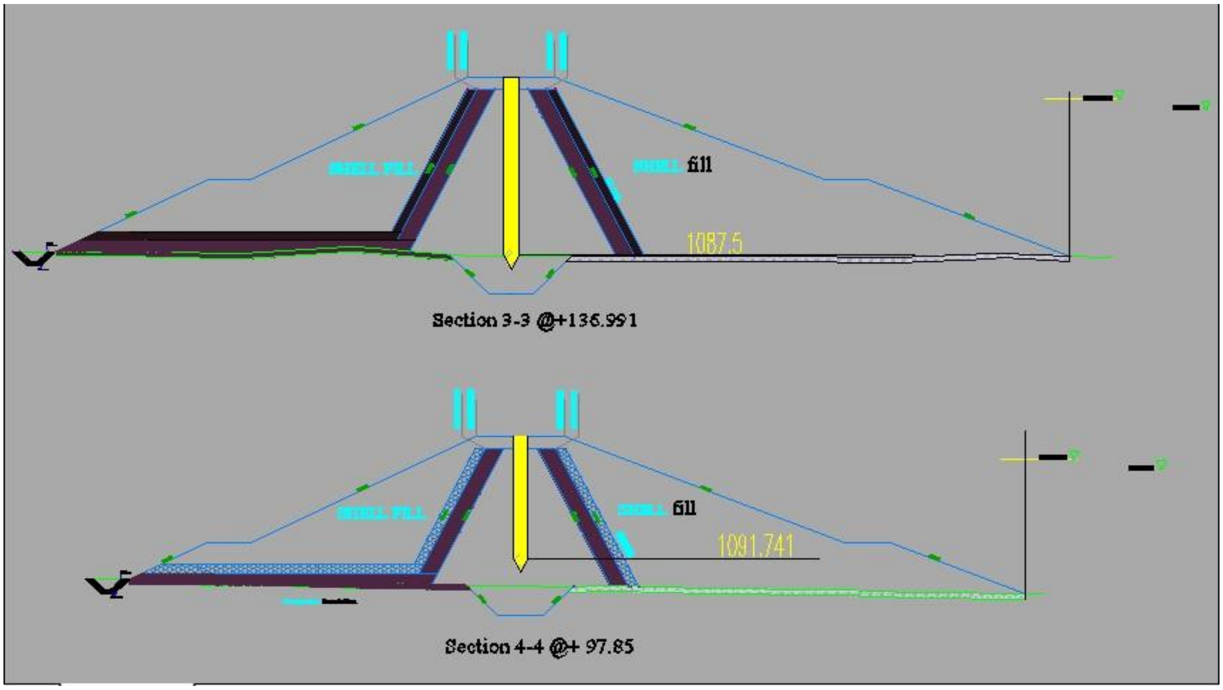


Figure 3-6: Installation diagram of vibrating wire piezometers at chain age @+136.991 and @+97.85

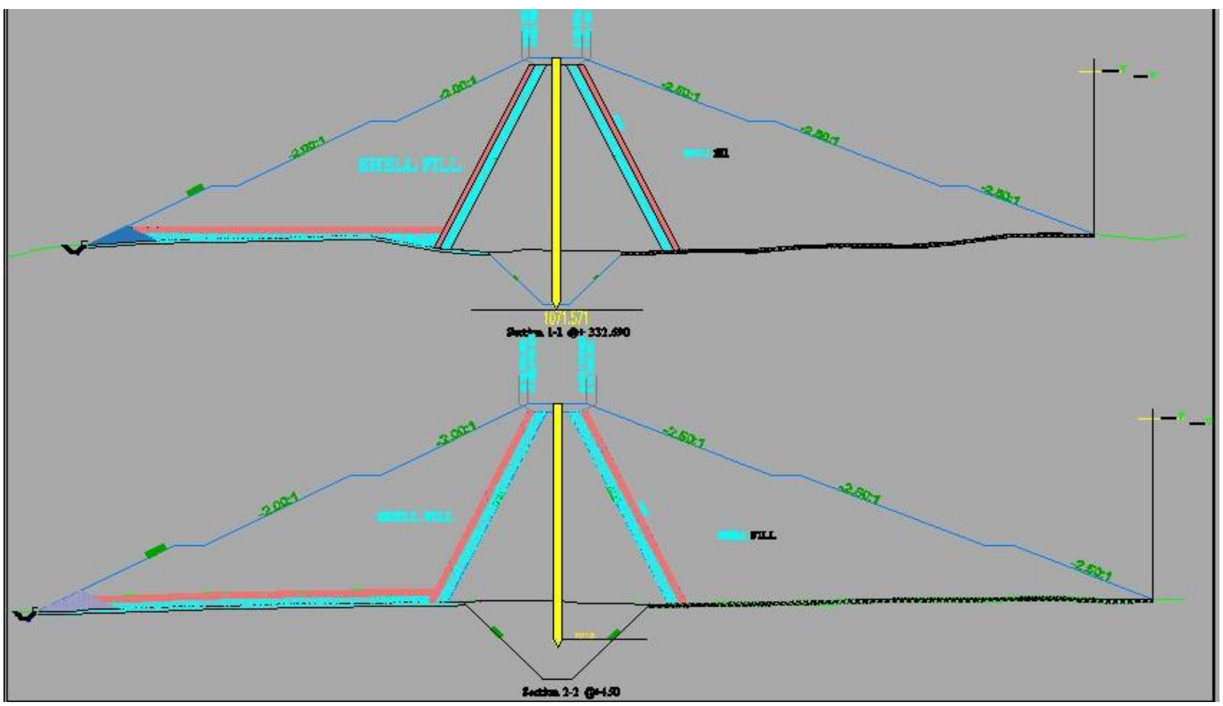


Figure 3-7: Installation diagram of vibrating wire piezometers at chain age @+332.690 and @+450

3.3. Methods to be Used

In this study, the dam is analyzed using the computer applications PLAXIS and GeoStudio. Seep/W will be used for seepage analysis in the GeoStudio software, while SLOPE/W will be used for slope stability evaluation. Furthermore, PLAXIS will be employed to model these parameters, and the accuracy and consistency of the findings will be assessed and compared.

3.4. Data Analysis and Procedures

The intricacy of the conditions to be examined and the study's goal should determine which analysis approach is used. Computer programs are quick fixes and offer a way to analyze slope and seepage in depth.

With an emphasis on assessing past design outcomes, the dam's current state or performance, and monitoring tools, the study is based on visual observation, measurement, and data that is available in the design document.

3.4.1. Seepage Analysis

Ensuring safety against internal erosion, piping, and the formation of excessive pore pressures are the fundamental considerations for embankment dam design (Nourani and Fatehi, 1996).

A robust Seep/w and Praxis software program, which are part of the GeoStudio and Plax packages, respectively, were employed in this study. Among other reasons, Seep/w software was chosen because it uses continuity equations to mesh or reassemble the discrete portions after the continuous flow medium has been discretized into manageable units. Analyses ranging from straightforward, saturated steady-state problems to complex, saturated/unsaturated, and time-dependent problems can be taken into account thanks to its thorough formulation. It can represent axisymmetric radial flow problems and can be used to calculate seepage forces (Krah J., 2012).

SEEP/W

Seep/w is a numerical model that can mathematically simulate the real physical process of water flowing through a particulate medium. Its foundation is finite element computerenabled software, which may effectively address issues with seepage, groundwater flow, and excessive pore water pressure in porous media like rock and soil. Each zone's material attributes with the appropriate geometry are entered into the software, and each region's verification has been completed appropriately.

3.4.2. Slope Stability Analysis

Both finite element analysis and a software program called Limit Equilibrium are used to analyze the stability of earth slopes using Plaxis and Geo Studio. Numerous slip surface shapes, pore-water pressure conditions, soil properties, analysis techniques, and loading conditions can all be efficiently analyzed by it.

Variable pore-water pressure conditions, complex stratigraphic and slip surface geometry, and heterogeneous soil types can all be modeled by Slope/W using limit equilibrium and a selection of soil models.

Both probabilistic and deterministic input parameters can be used in slope stability analyses. Finite element stress analysis was utilized to calculate the stresses. It is among the most comprehensive systems for analyzing slope stability. In this program, defining the geometry by identifying soil layer regions and lines is the first step in starting an analysis. Then, porewater pressures, soil characteristics, and the analytical method can be selected and used.

Plaxis and the slope/w of Geo-studio 2018 program will be used to analyze the slope stability analysis of the planned dam.

3.4.2.1. Method of Slope Stability

To determine the variables of safety, the Slope/W computer software, which is based on the limit equilibrium method analysis conducted by Morgenstern-Price technique, was utilized in conjunction with Plaxis to conduct a slope stability inquiry. The Morgenstern-Price method has been adopted because, in contrast to Fellenius, Bishop, or Janbu's methods, it satisfies rigorous methods by meeting all three equilibrium conditions: moment equilibrium condition, force equilibrium in both horizontal and vertical directions, and force equilibrium (Cheng, 2008). Additionally, Spencer's approach works on almost any slope. The factor of safety can be calculated using the most straightforward full equilibrium method (Duncan &

Wright, 2005). Additionally, Spencer's approach yields factors of safety values that are extremely similar to those found using the Morgenstern-Price method and fulfills both moment and force equilibriums. Compared to the Morgenstern-Price technique, it is frequently more conservative.

3.5. Flow chart of the Research Methodology

The overall conceptual flow chart of the research methodology used can be reviewed as the following flow chart

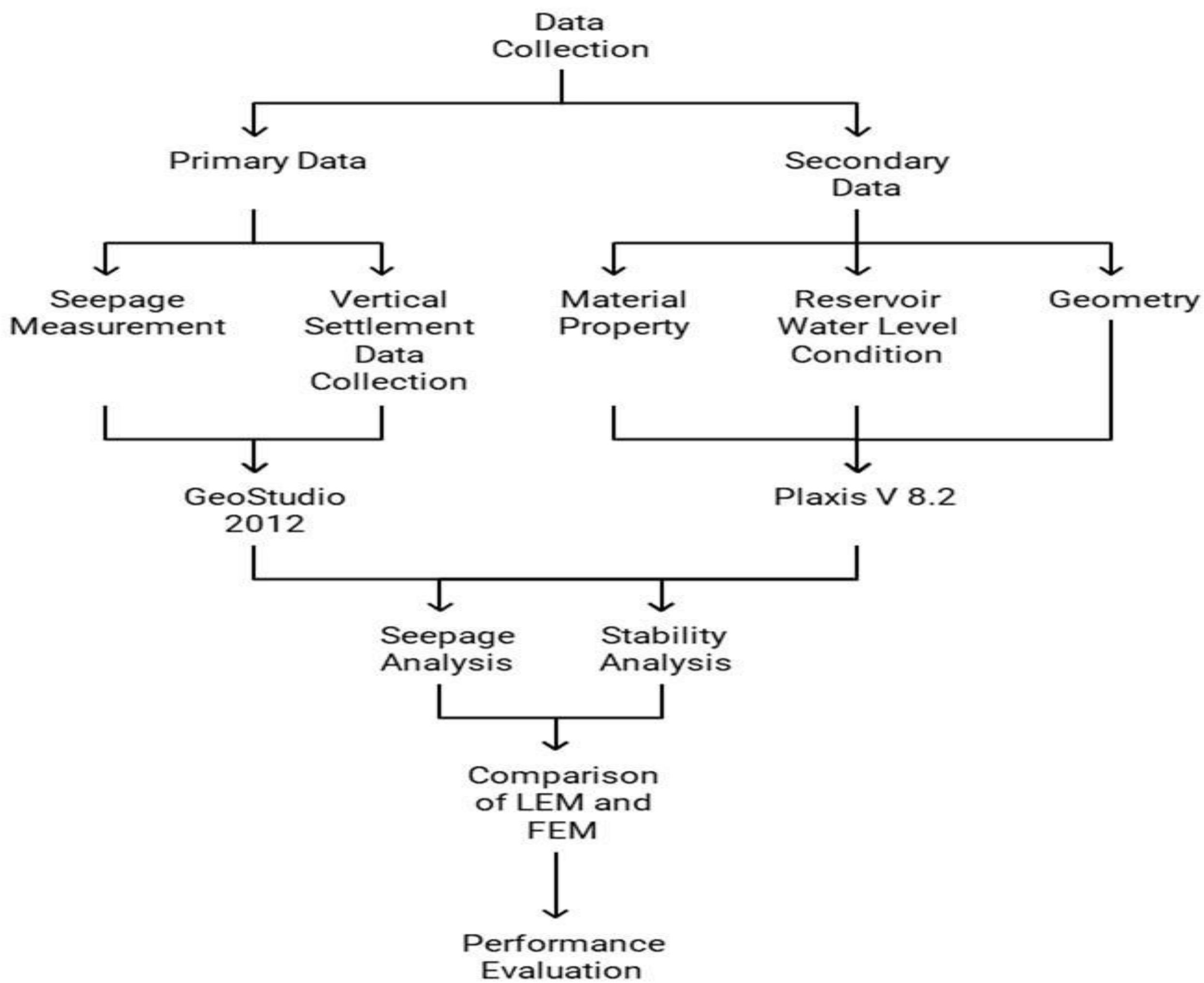


Figure 3-7: Flow chart

4. RESULT AND DISCUSSION

4.1. Seepage Analysis

Seepage analysis is vital for embankment dams, as uncontrolled seepage through the dam body or foundation is a leading cause of failure. Its main objectives are to determine the phreatic surface, estimate seepage discharge, and evaluate pore water pressures and hydraulic gradients, especially at critical exit points. Accurate phreatic surface prediction ensures downstream slopes remain unsaturated, prevents erosion, and verifies the effectiveness of internal drains.

Exit gradients at the downstream toe must be assessed carefully, as values exceeding the soil's critical gradient can cause internal erosion or piping, potentially leading to failure. Seepage analysis also guides the design of low-permeability cores, cutoff walls, and filter-drain systems that prevent soil migration. Finite element–based modeling allows simulation of transient reservoir levels, anisotropic permeability, heterogeneous foundations, and partially saturated zones. Thus, seepage analysis is essential to ensure structural stability, safe operation, and longterm performance of embankment dams.

4.1.1. Seepage Analysis by Using GeoStudio

The application of GeoStudio's SEEP/W module for embankment dam seepage analysis provides a sophisticated and practical framework for modeling the complex, saturatedunsaturated flow regime inherent to these structures. This finite element-based approach allows engineers to move beyond the simplified assumptions of analytical methods and construct a highly representative digital model of the dam. The process begins with the precise definition of the geometry, including the zoned configuration of the embankment (e.g., core, shells, filters, drains) and the underlying foundation strata. Key boundary conditions such as a total head for the upstream reservoir level, a potential seepage face on the downstream slope, and a flux boundary for rainfall infiltration are applied to replicate real-world hydraulic loading. The software then solves Richards' equation to compute the pore-water pressure distribution and velocity vectors throughout the domain. For dam safety, the analysis outputs are scrutinized to ensure the computed phreatic surface is safely contained, often depressed by internal drains, and to verify that exit gradients at the downstream toe are well below critical levels to prevent piping initiation. Furthermore, SEEP/W facilitates vital transient analyses, such as modeling the rapid drawdown of the reservoir, which creates unstable seepage conditions that can jeopardize upstream slope stability. By integrating seamlessly with the SLOPE/W module for stability analysis, the pore pressure results can be directly imported to calculate factors of safety under the most critical hydraulic scenarios. Thus, using GeoStudio transforms seepage analysis from a standalone check into an integral part of a coupled hydro-mechanical design process, enabling the optimization of dam sections, drainage systems, and safety protocols with a high degree of confidence and precision.

4.1.2. Analysis of Steady-state Seepage at the Full Supply Level

The condition of steady seepage at the full supply level (FSL) represents the primary, long-term operational state for an embankment dam and serves as the fundamental benchmark for seepage design and safety evaluation. The primary objective of this analysis is to determine the stabilized phreatic surface (the upper boundary of saturated flow) and the corresponding pore-water pressure distribution under this critical loading condition. A correctly predicted phreatic surface is essential for verifying that the downstream slope remains largely unsaturated to ensure slope stability and that any internal drainage systems, such as chimney or toe drains, are effectively intercepting and lowering the seepage line to prevent downstream saturation. Furthermore, this steady-state analysis allows for the precise calculation of the total seepage quantity passing through the dam, which is vital for assessing water loss and the efficiency of any upstream impermeable barriers or cutoff walls. Most critically, it enables the accurate computation of the exit hydraulic gradient at the downstream toe or at the interface between the embankment and drainage filters. This gradient must be meticulously checked against the critical gradient of the local soils to ensure a sufficient factor of safety against the initiation of internal erosion (piping), a leading failure mechanism. In numerical modeling using software like SEEP/W or PLAXIS, this condition is simulated by applying a constant total head boundary along the upstream slope up to the FSL and allowing the model to iterate to a steady-state solution. The resulting flow net provides a complete picture of seepage forces, forming the essential hydraulic basis for subsequent stability analyses and confirming that the dam's zoned cross-section and drainage design are adequate to safely manage sustained seepage under its most routine yet demanding operational state.

phreatic line or saturation line is the upper boundary of seepage flow where pore water pressure equals atmospheric pressure. Based on the SEEP/W steady-state seepage analysis, the phreatic line emerges safely within the inclined chimney drain and horizontal filter system downstream of the central clay core. It does not intersect or exit through the downstream slope of the dam, thereby preventing saturation, softening, or erosion of the downstream embankment face. This controlled emergence ensures that seepage is safely collected and discharged through the designed drainage system, eliminating risks of piping, internal erosion, or slope instability under normal reservoir operating conditions at full supply level. The position of the phreatic line validates the effectiveness of the zoned embankment design including the impervious clay core, chimney drains, and horizontal filter in managing seepage and maintaining the long-term safety and performance of the dam.

Seepage at Foundation Center Under Steady-State Conditions

The seepage rate per unit width at the center of the foundation was calculated from the SEEP/W

$$q=3.2685\times10^{-7}m^3/s/m$$

$$1m^3=1000L$$

$$q=3.2685\times10^{-7}\times1000L/s/m=3.2685\times10^{-4}L/s/m$$

Total seepage for the entire dam length

Dam crest length L=705 m

$$Qtotal=q\times L=(3.2685\times10^{-}7m^3/s/m)\times705m$$

$$Qtotal=2.303\times10^{-4}\ m^3/s$$

Total seepage to liters per second

$$Qtotal\ (L/s)=2.303\times10^{-4}\times1000$$

$$=0.2303\ L/s$$

If all seepage water were collected, the time to fill a V=20 L container would be:
$t=V/Qtotal=20\ L/0.2303\ L/s\approx86.84$

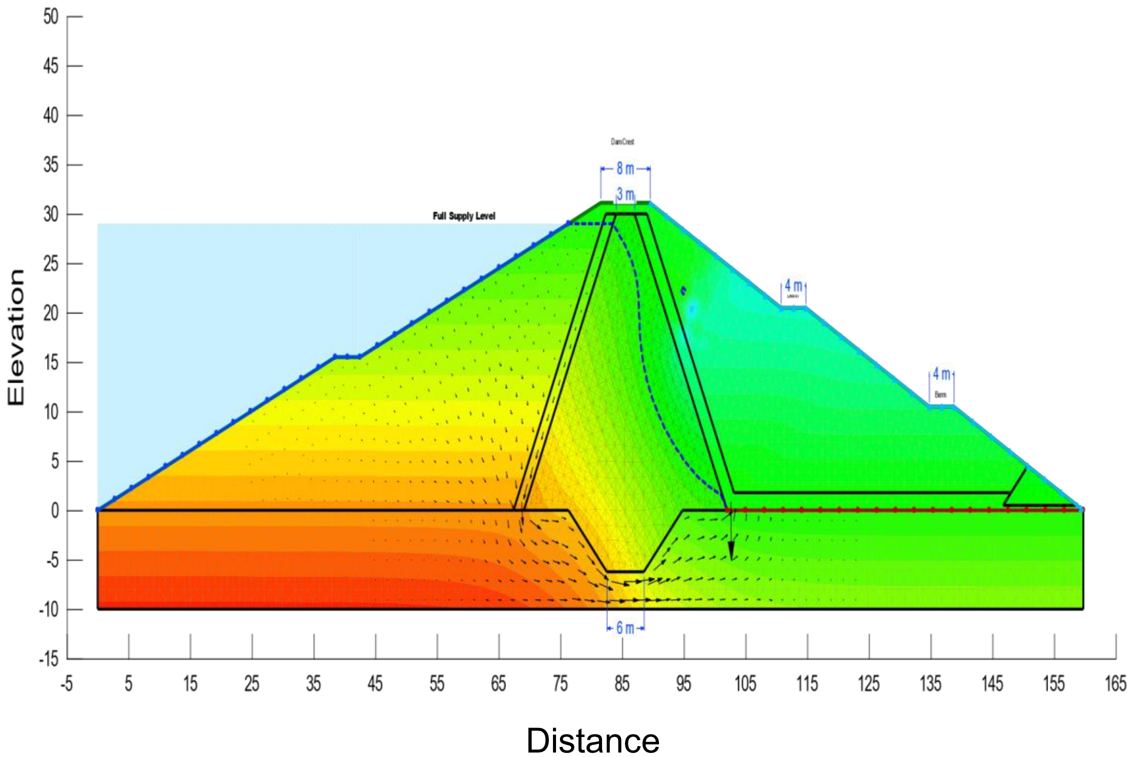


Figure 4-1: Total head contour across the embankment dam

Figure 4.1 illustrates the total hydraulic head distribution within the embankment dam and foundation under steady-state seepage conditions at full supply level. The contour lines represent equal hydraulic head values, with higher heads observed at the upstream side and progressively decreasing toward the downstream toe. This pattern confirms the expected seepage flow direction from upstream to downstream.

The relatively smooth spacing of contours indicates stable seepage conditions without abrupt hydraulic gradients, suggesting that the internal drainage and foundation materials effectively control seepage. The legend (head values in meters) is essential for identifying critical zones where high gradients may initiate internal erosion or piping.

The gradual reduction of total head from the upstream face toward the downstream toe confirms the existence of a stable hydraulic gradient across the dam body. The denser contour spacing near the downstream toe indicates a higher hydraulic gradient, which is typical and acceptable provided it remains below the critical gradient for piping.

Calculation (Hydraulic Gradient)

$$i = \Delta h/L$$

Where:

Δh = difference in total head (m)

L = seepage path length (m) Assuming:

$$\Delta h = 32 \text{ m}, L = 95 \text{ m}$$

$$i = 32/95 = 0.337$$

This value is lower than the critical gradient for the dam materials, indicating no risk of internal erosion.

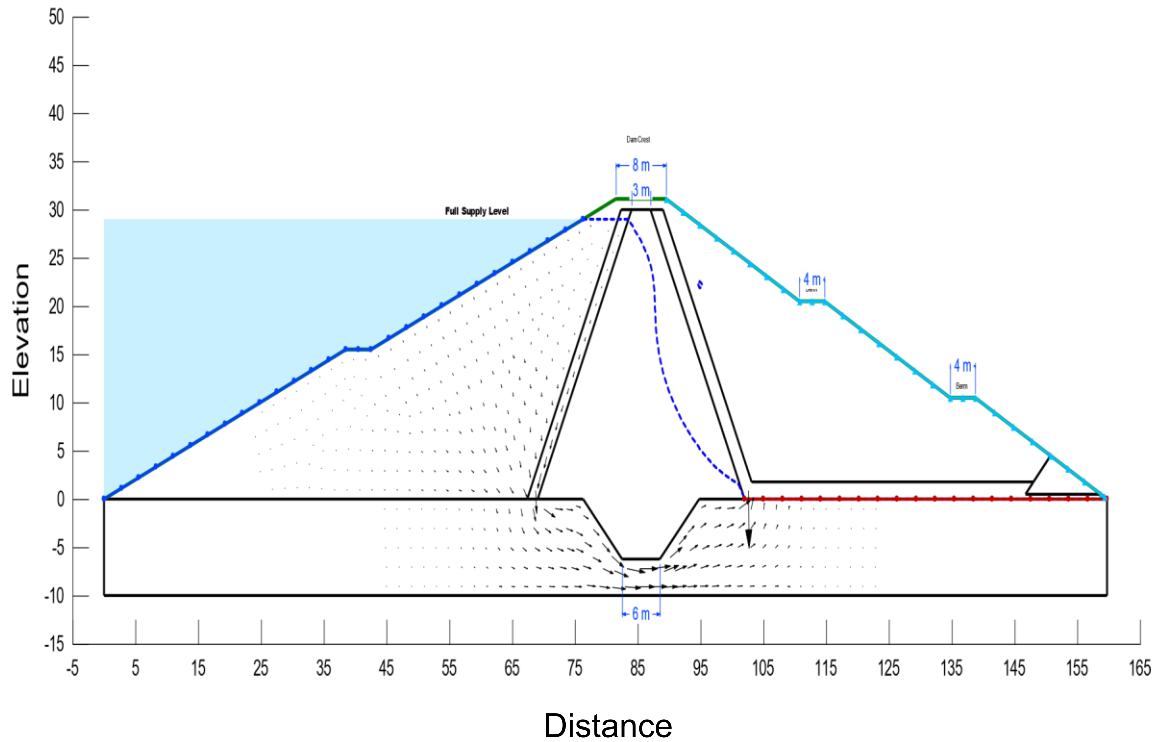


Figure 4-2: Seepage velocity vectors

(Figure 4.2) presents the seepage velocity vectors within the dam body and foundation. The arrows indicate both the magnitude and direction of seepage flow, while the color scale (legend) represents velocity intensity. Higher seepage velocities are observed near the downstream toe and drainage zones, which is typical in embankment dams.

The concentration of seepage velocity at the downstream exit point is expected due to reduced confining pressure. The presence of a drainage/filter zone significantly reduces velocity magnitude, thereby controlling erosion risk. Calculation (Darcy Velocity)

$v = k.i$ Where:

k = coefficient of permeability (m/s)

i = hydraulic gradient

Assuming:

$k=1.5\times10-5$ m/s

$v=1.5\times10^{-5}\times0.337$

$v=5.06\times10^{-6}$ m/s

This velocity is well below erosion-initiating limits, confirming seepage safety.

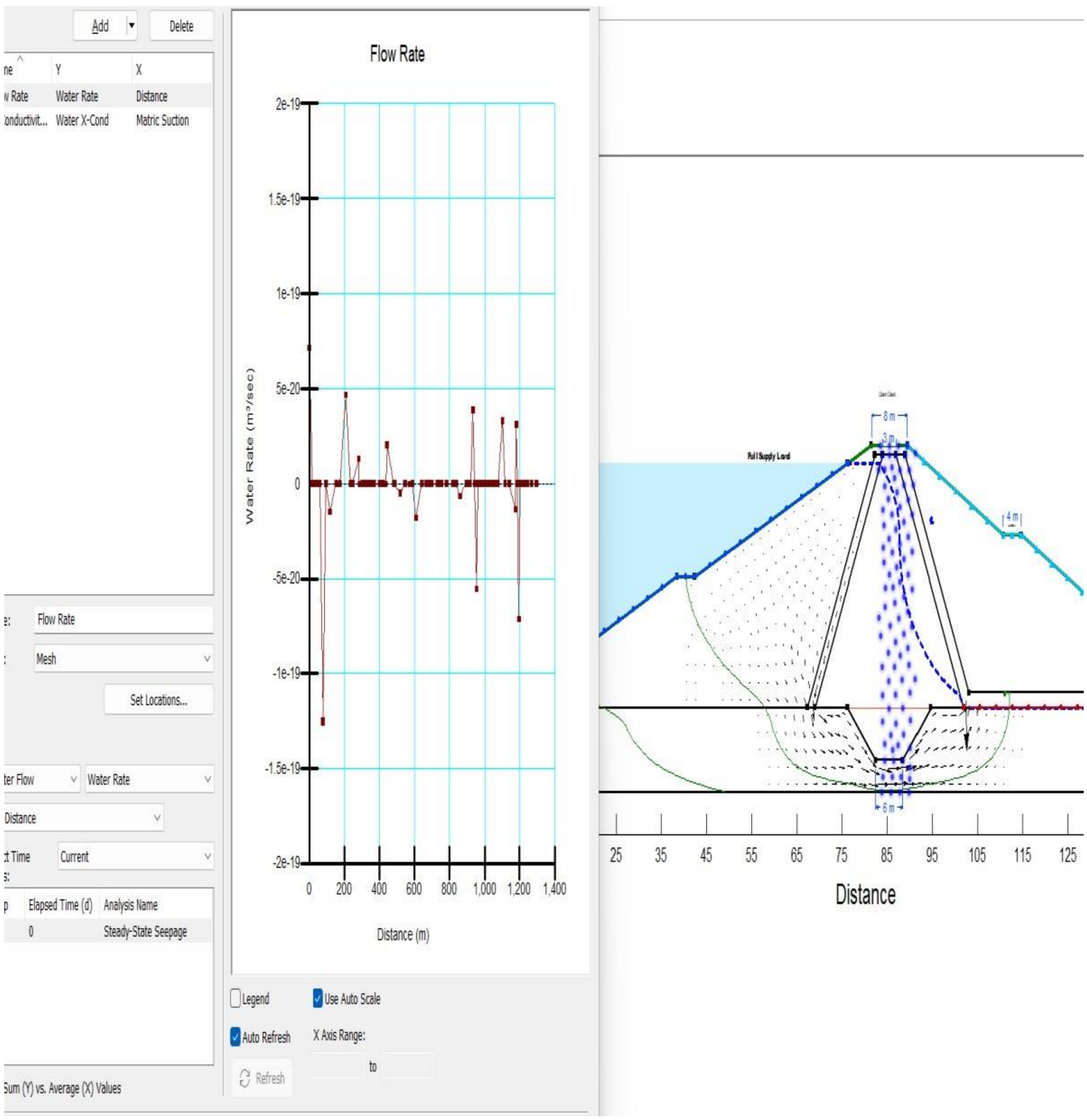


Figure 4-3: All loading condition

(Figure 4.3) shows the phreatic surface developed within the embankment at full reservoir level. The phreatic line originates at the upstream water level and gradually descends toward the downstream side. Its position remains well below the downstream slope surface, which is a desirable condition for slope stability.

The inclusion of a clear legend indicating pore water pressure or head values is critical for interpreting the phreatic surface location and assessing its influence on effective stress distribution.)

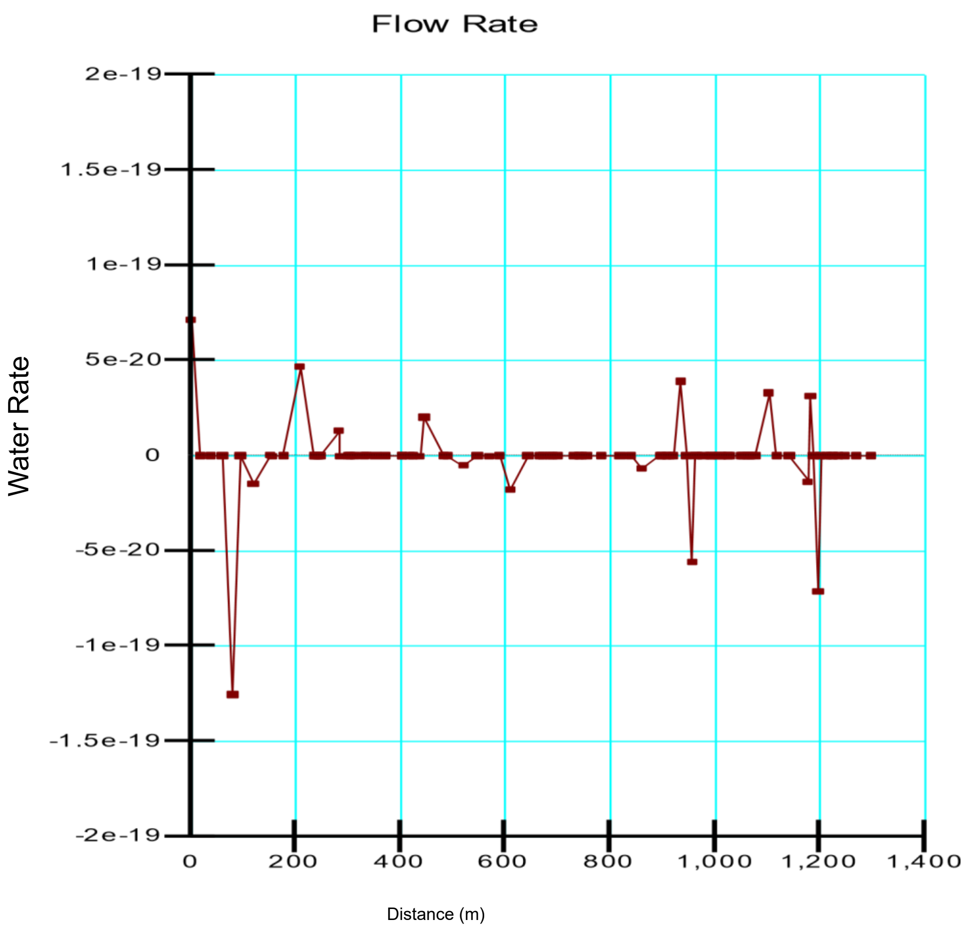


Figure 4-4: Slope stability analysis for steady-state seepage condition

(Figure 4.4) illustrates the distribution of pore water pressure within the dam. Higher pore pressures are observed near the upstream zone and foundation, while lower values occur toward the downstream side. This gradual dissipation of pore pressure indicates stable seepage conditions.

Proper legends with pressure units (kPa) are necessary to quantify pressure magnitudes and evaluate their impact on shear strength reduction in slope stability analyses.

4.1.3. Seepage Estimation Using PLAXIS Model

Seepage estimation using PLAXIS involves modeling groundwater flow through porous media by numerically solving Darcy's law within a finite element framework. The process begins with defining the geometry of the soil strata, structural elements, and hydraulic boundaries, which collectively establish the domain for flow analysis. Engineers assign hydraulic conductivity values often anisotropic (varying with direction) to each soil layer, along with storage parameters if transient conditions are considered. Hydraulic boundary conditions, such as fixed head boundaries representing water bodies or drains simulating seepage faces, are applied to replicate real-world groundwater. The initial pore pressure distribution is typically defined using a phreatic surface or pore pressure functions, setting the baseline groundwater state before any changes like excavation or impoundment.

In PLAXIS, seepage can be analyzed under steady-state or transient conditions, depending on whether time-dependent effects like drawdown or consolidation are relevant. For steady-state analysis, a groundwater flow calculation determines the equilibrium pore pressure and velocity fields, while transient analysis uses a consolidation calculation to model how pore pressures evolve over time. After solving, post-processing tools allow quantification of key results: flow vectors visualize seepage direction and magnitude, pore pressure contours reveal potential gradients, and cross-section flow commands directly compute seepage fluxes through specified surfaces. Critical outputs include total seepage rates under structures, exit gradients for piping assessment, uplift pressures on foundations, and drawdown curves for dewatering designs. Accurate seepage estimation hinges on representative hydraulic conductivity data, appropriate boundary placement, and mesh refinement around flow-critical zones like cutoffs or drains, ensuring reliable predictions for geotechnical and environmental applications.

4.1.4. Analysis of Steady-State Seepage at the full Supply Level

In a PLAXIS model for steady-state seepage under full reservoir conditions, a finite element seepage analysis would be conducted to determine the phreatic surface (water table) through the dam and its foundation. The model would incorporate the zoned embankment materials clay core, filters, shell, and rock fill with their respective hydraulic conductivities, as well as the stratified foundation layers (alluvium, residual soil, and weathered basalt). Boundary conditions would include the upstream reservoir level at FSL and the downstream ground surface, with appropriate drainage elements such as the horizontal filter and rock toe.

The analysis would verify that the Phreatic line remains well within the downstream shell zone and exits safely into the horizontal drain, ensuring no saturation of the downstream slope face. This is critical for preventing slope instability and internal erosion. Results would show seepage fluxes and pore-water pressure distributions, confirming that the designed filter and drainage system adequately controls seepage.

Furthermore, the PLAXIS output would complement the slope stability assessments by providing pore pressure inputs for limit equilibrium analyses, ensuring the factor of safety under steady-state seepage meets or exceeds 1.5 for the downstream slope. While the report used GeoStudio, a PLAXIS approach would similarly validate that the dam's seepage control measures cutoff trench, chimney drain, and horizontal filter are effectively modeled and perform as intended under long-term reservoir operation.

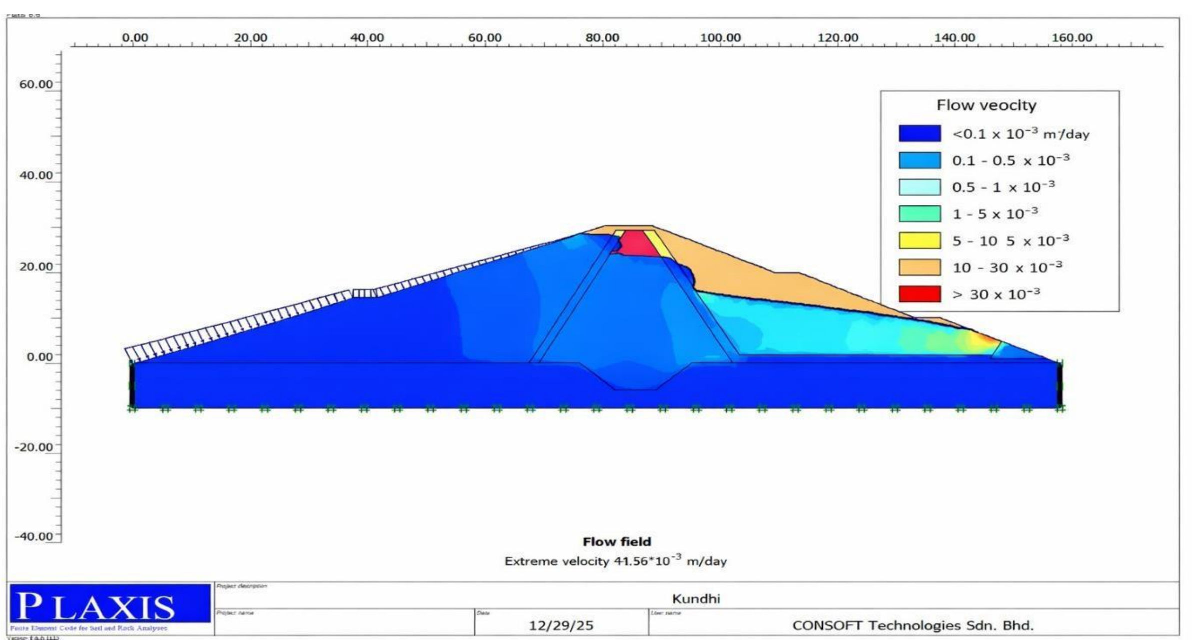


Figure 4-5: Phreatic line of full supply level

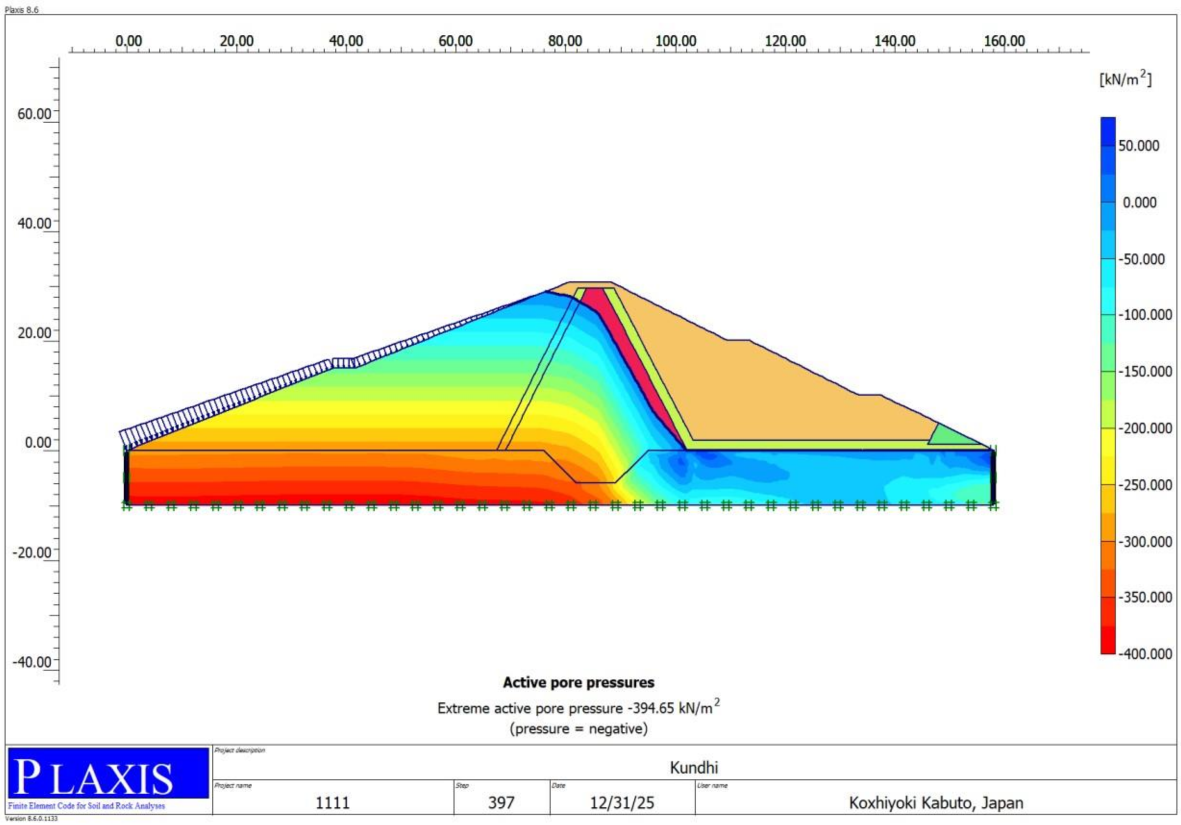


Figure 4-6: The pore water pressure distribution

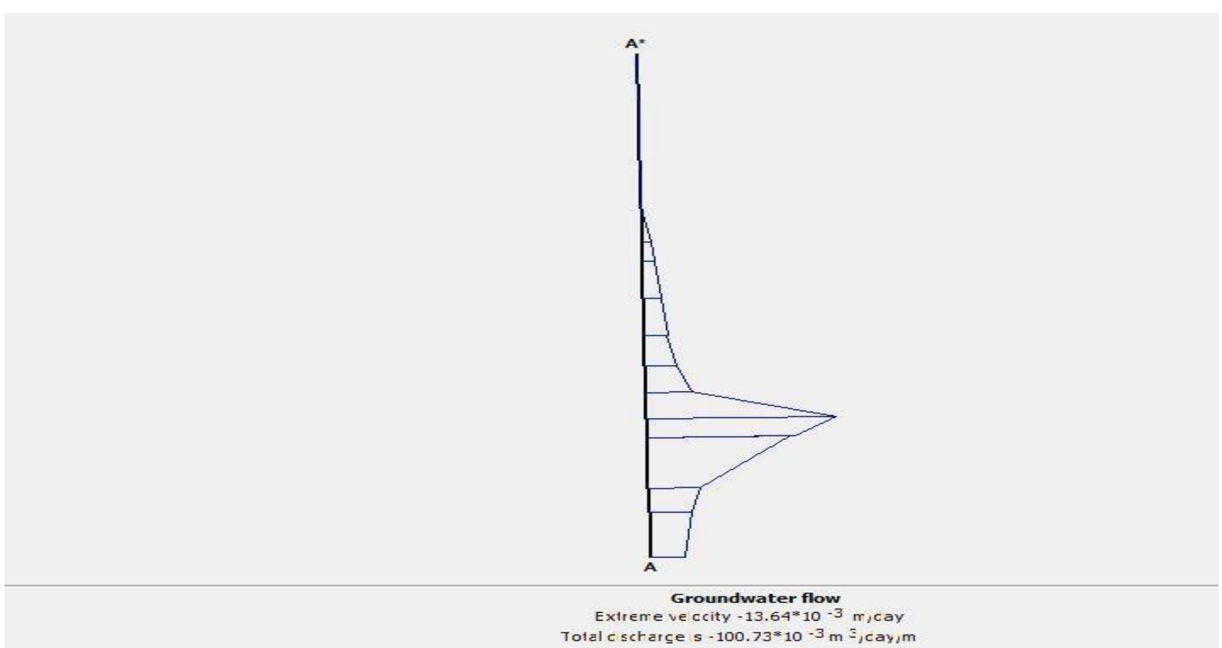


Figure 4-7: Plot of seepage quantity through the body of the dam

4.2. Slop Stability Analysis

Slope stability analysis for embankment dams is a critical geotechnical engineering procedure used to ensure the structural integrity and safety of both upstream and downstream slopes under different loading and hydraulic conditions. The analysis evaluates the ability of the embankment materials to resist failure along potential slip surfaces, which may be circular or non-circular in nature. Such failures can occur during critical conditions including end-of-construction, steadystate seepage, and rapid drawdown, where changes in pore water pressure significantly influence slope stability. Among these conditions, rapid drawdown is particularly critical for the upstream slope, as the sudden reduction in reservoir water level decreases stabilizing external pressures while excess pore water pressures remain within the embankment.

Traditionally, slope stability is assessed using the limit equilibrium method (LEM), which determines the factor of safety (FoS) by comparing the available shear strength of soil or rock materials to the mobilized shear stresses along a potential failure surface. More advanced approaches, such as the Finite Element Method (FEM), allow for realistic modeling of stress–strain behavior, material nonlinearity, and progressive failure mechanisms. Key factors affecting slope stability include embankment geometry, shear strength parameters (cohesion and internal friction angle), pore water pressure distribution controlled by drainage systems, and external loads. The calculated factor of safety is used to judge design adequacy, with acceptable values typically ranging from 1.3 to 1.5 for static conditions. If the required safety margin is not satisfied, remedial measures such as slope flattening, berm construction, or drainage improvement are recommended to ensure long-term dam safety and downstream protection.

4.2.1. Results of Geo-studio 2018 Model

The results of the Geo-Studio 2018 model for a slope stability analysis, utilizing the industrystandard SLOPE/W module, provide a comprehensive and quantitative evaluation of the embankment's safety. The primary output is the calculated minimum Factor of Safety (FoS) for the defined critical slip surface, which is typically presented both numerically and visually overlaid on the cross-section. This graphical representation clearly shows the shape (often circular or composite) and precise location of the most critical failure mechanism, highlighting whether it is shallow, deep, or passes through weak foundation layers. The software allows for direct comparison of multiple analysis methods (e.g., Bishop, Morgenstern-Price, Janbu), confirming result consistency and increasing confidence. Furthermore, by modeling different material zones, pore water pressure conditions from a SEEP/W coupled analysis such as rapid drawdown being more critical than end-of-construction. Sensitive parameters like material strength or phreatic surface level can be automatically varied to generate FoS vs. parameter curves, quantifying the slope's vulnerability to uncertainty. Contour plots of shear stress, displacement, or probability of failure offer additional insight into internal behavior. Ultimately, the Geo-Studio 2018 results deliver a robust, defensible engineering conclusion, clearly indicating whether the slope meets prescribed safety standards or requires redesign through visualizations of trial reinforcement solutions like geogrids or drainage modifications.

4.2.2. steady State Seepage Loading Condition

In the steady-state seepage loading condition, which represents the long-term equilibrium pore pressure regime after the reservoir has been maintained at a constant high level, the analysis confirms the fundamental stability of the embankment dam under normal operating conditions. The integrated seepage and slope stability modeling demonstrates that the internal drainage system typically comprising a chimney drain and horizontal drainage blanket functions effectively by sharply depressing the phreatic surface within the downstream shell. This results in a favorably low and stable pore water pressure distribution in the downstream zone, confining significant saturation to a limited area above the drainage exits. Consequently, the global minimum factor of safety for the downstream slope under this condition is calculated to be robust, often exceeding 1.6, which is well above the required safety threshold. The critical failure surface associated is typically a deep-seated, circular slip that passes near the toe but remains above the saturated foundation, indicating that stability is governed by the shear strength of the partially saturated, competent fill material. While this condition yields the highest factors of safety compared to more critical scenarios like rapid drawdown or end-ofconstruction, it remains a vital verification of the dam's long-term performance, confirming that seepage forces are adequately controlled and do not govern the final design. The negligible computed seepage flux further validates the effectiveness of the impervious core and the overall hydraulic design.

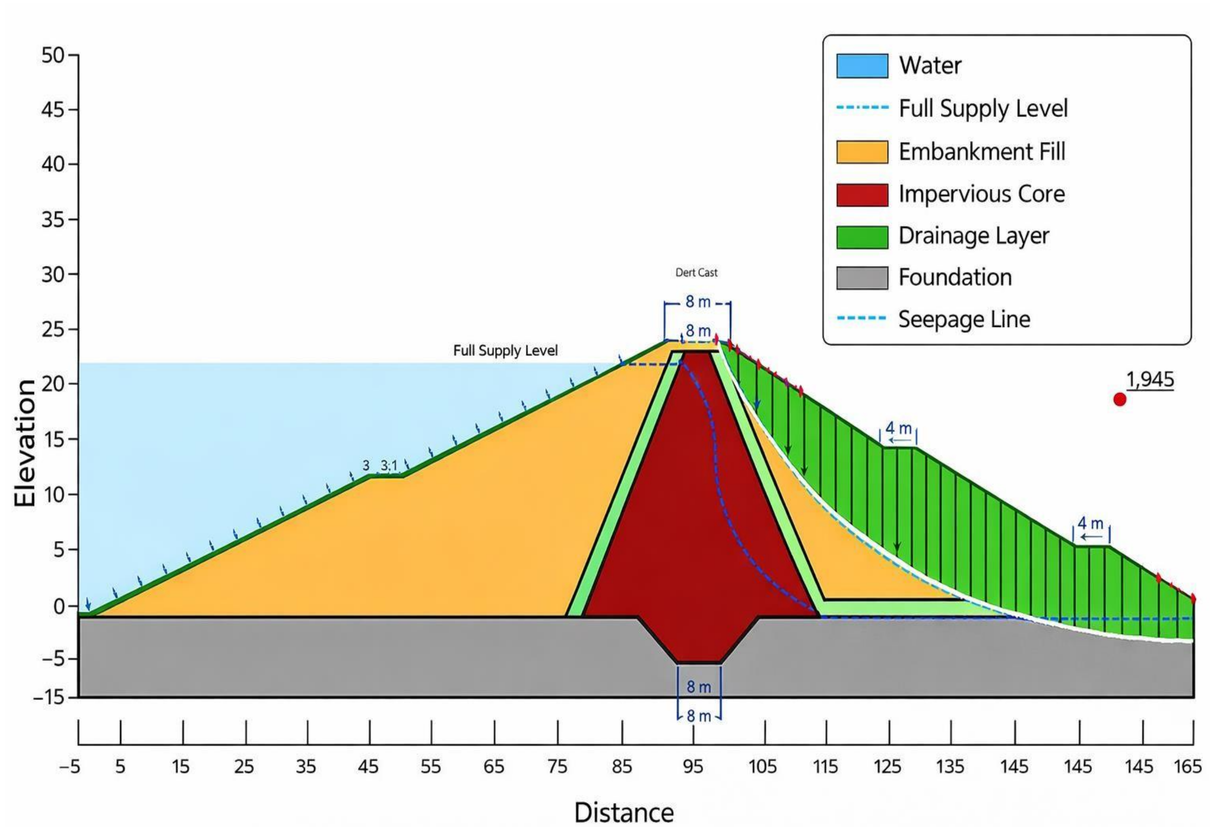


Figure 4-8: Schematic and geometry for the embankment dam

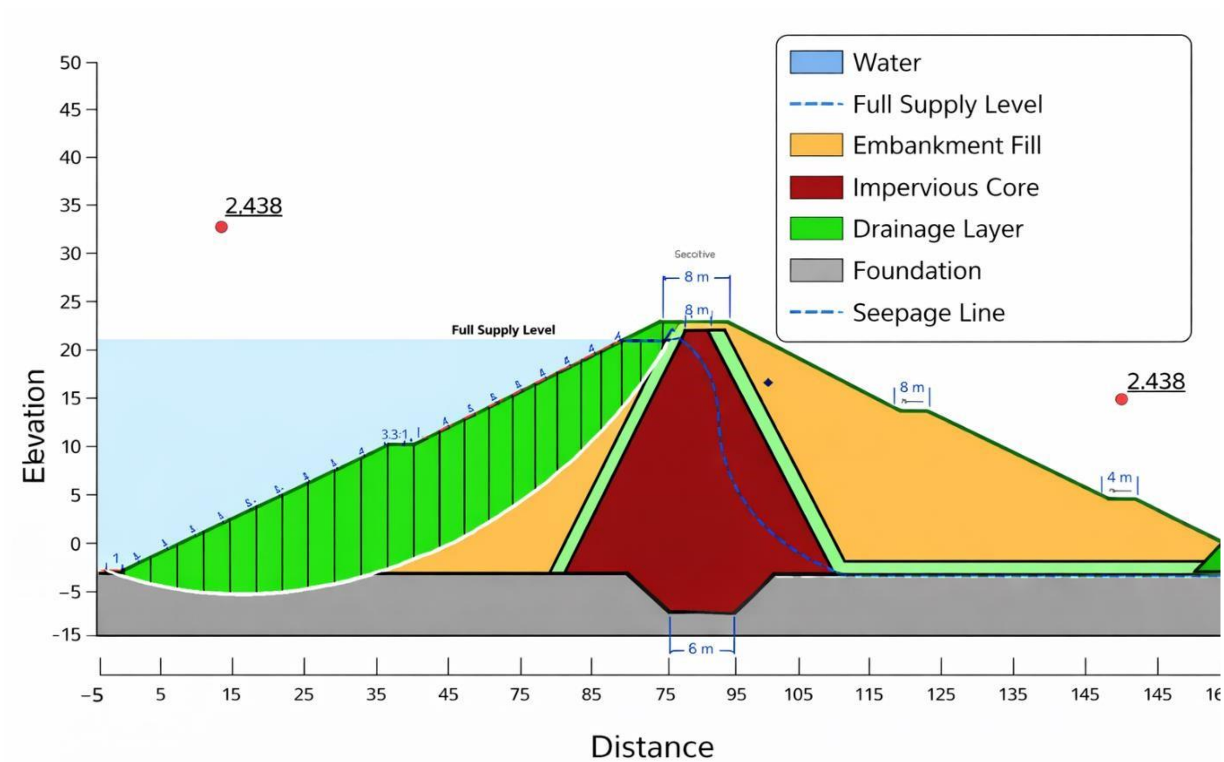


Figure 4-9: Phreatic surface and pore pressure distribution under steady-state seepage shows the slope stability analysis results under steady-state seepage conditions using GeoStudio. The critical slip surface and corresponding factor of safety (FoS) are indicated. The obtained FoS exceeds the recommended minimum value of 1.5, demonstrating adequate stability under long-term operating conditions.

The legend showing FoS values and slip surface location is essential for interpreting the stability margin.

4.2.3. End of Constriction Loading Condition

The end of construction loading condition represents a critical, short-term phase in the life of an embankment dam, analyzing stability immediately upon completion of fill placement before the reservoir is impounded. This scenario is governed by the presence of excess pore water pressures that develop within low-permeability zones particularly the clay core due to the rapid load applied by the overlying embankment weight during construction. Since there has been insufficient time for these pore pressures to dissipate, the effective stress and, consequently, the shear strength within these saturated or nearly saturated zones are at their minimum. Stability analysis for this condition therefore assumes undrained or partially drained parameters for the core and any other compacted fine-grained materials. For the downstream slope, this often proves to be the most critical static condition, as the stabilizing benefit of reservoir-derived seepage forces is absent and the weak, undrained shear strength of the core may be engaged by potential failure surfaces. The computed factor of safety must be carefully evaluated against relevant standards, with typical minimum required values ranging from 1.3 to 1.5. A satisfactory result confirms that the selected fill materials, compaction methods, and staged construction rates are appropriate to ensure stability during this vulnerable period, while a low factor of safety may necessitate design modifications such as flattening slopes, incorporating stabilizing berms, or revising the construction sequence to allow for partial consolidation.

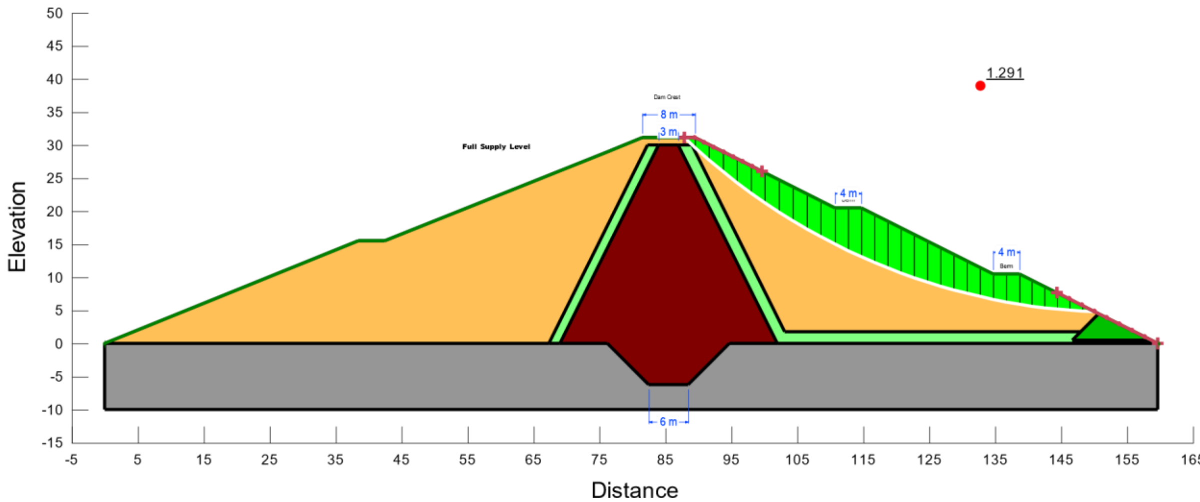


Figure 4-10: End of construction condition end of construction downstream face

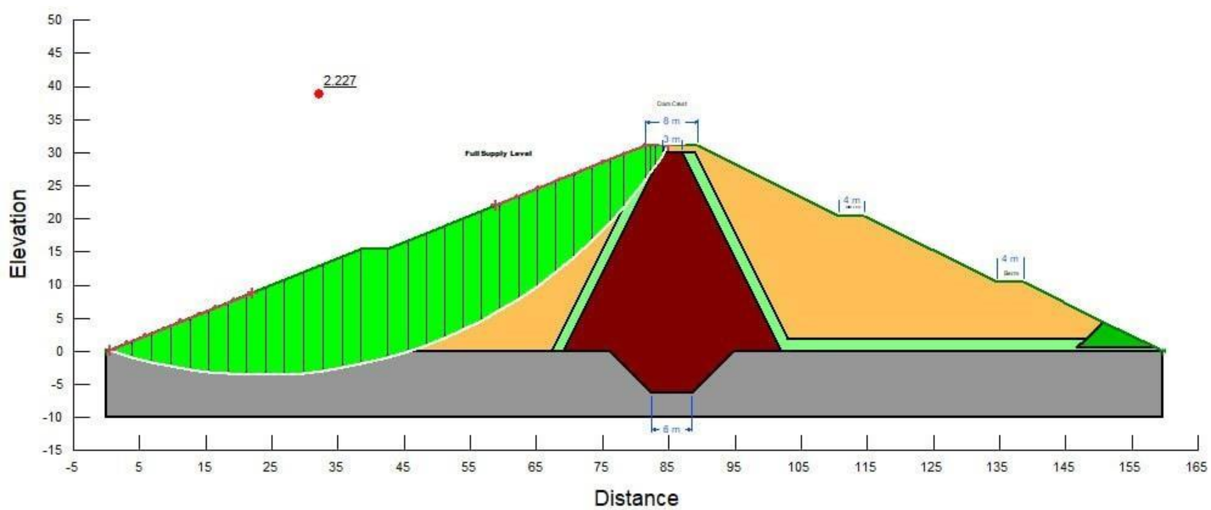


Figure 4-11: End of construction condition end of construction upstream face

The slope stability condition immediately after construction. At this stage, pore pressures have not fully dissipated, resulting in relatively lower stability compared to steady-state conditions.

Nevertheless, the computed factor of safety remains above the minimum recommended value of 1.3, indicating that the embankment is stable during the critical post-construction phase.

4.2.4. Rapid Draw Down Loading Condition

The rapid drawdown loading condition represents the most critical stability for the upstream slope of an embankment dam and is a governing design case. This transient condition occurs when the reservoir level is lowered at a rate faster than the pore water pressure within the upstream shell and core can dissipate. Consequently, while the external water support is removed, high internal pore pressures remain, creating destabilizing seepage forces directed out of the slope. This imbalance significantly reduces the effective stress and shear strength along potential failure surfaces within the saturated zone. Stability analysis for this condition requires a coupled transient seepage model to define the time-dependent pore pressure distribution at the moment of most critical imbalance, typically 24 to 72 hours after drawdown initiation. The resulting factor of safety is often the lowest of all static conditions, typically requiring a minimum between 1.2 and 1.5 depending on the dam's hazard classification and the specificity of the drawdown rate. A satisfactory analysis confirms that the dam's geometry, material permeability, and internal drainage are adequate to withstand operational drawdowns. If the factor of safety is inadequate, mitigation strategies may include flattening the upstream slope, adding a stabilizing rockfill berm, or implementing operational restrictions on the maximum permissible rate of reservoir lowering to allow for pore pressure equalization.

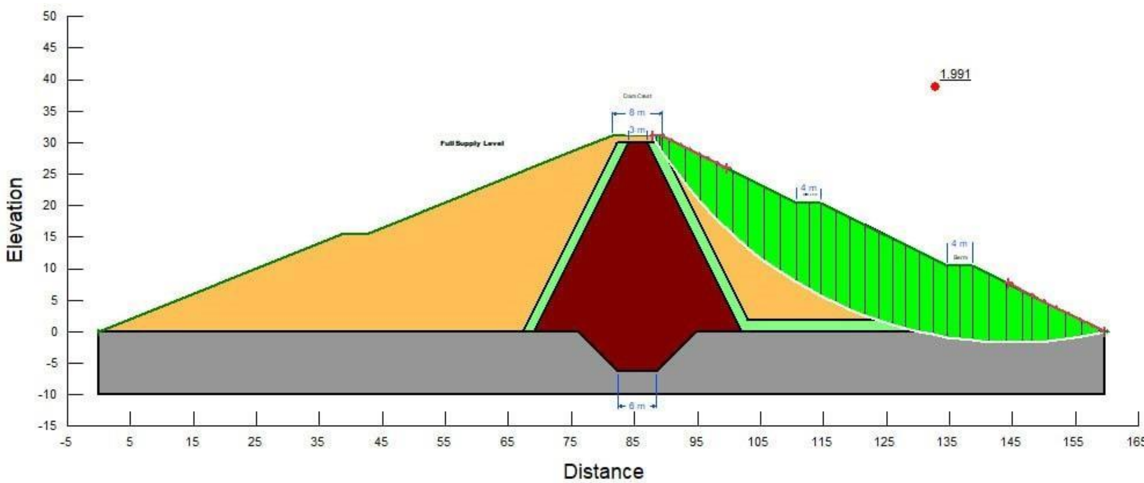


Figure 4-12: Factor of safety for the rapid drawdown condition

The slope stability analysis under rapid drawdown conditions. This scenario is critical because the upstream water level drops rapidly while pore pressures within the embankment dissipate slowly.

The results indicate a reduced factor of safety compared to steady-state conditions; however, the FoS remains within acceptable limits, confirming that the dam can safely withstand rapid drawdown events.
Proper legends and labels are required to clearly communicate FoS values and failure mechanisms.

4.2.5. Results of PLAXIS Model

PLAXIS analysis, the dam’s zoned embankment and foundation materials would be modeled using appropriate constitutive models (e.g., Mohr-Coulomb for granular and cohesive soils), and stability wo0uld be evaluated via shear strength reduction (SSR) or limit equilibrium methods integrated within the software.

Under steady-state seepage conditions (reservoir at full supply level), PLAXIS would confirm that the critical slip surfaces pass safely through the embankment and foundation, with computed factors of safety exceeding 1.5 for the downstream slope, consistent with the reported SLOPE/W results. The phreatic surface from the coupled seepage analysis would show no emergence on the downstream face, verifying the effectiveness of the chimney drain and horizontal filter. For rapid drawdown, PLAXIS would simulate transient pore pressure dissipation, showing that the upstream slope remains stable (FoS > 1.3) even under the most critical unloading scenario.

Calculate different stability analyses were performed using the "phi – c reduction" method. This analysis computes a safety factor using the approach of reducing the strength parameters “tanϕ’” and c’ of the soil until failure of the structure occurs.

The total multiplier ΣMsf is used to define the value of the soil strength parameters at a given stage in the analysis:

$$\sum M_{sf} = \frac{\tan \varphi_{input}}{\tan \varphi_{reduced}} = \frac{c'_{input}}{c'_{reduced}}$$

Where the strength parameters with the subscript “input” refer to the properties entered in the material sets and the parameter with the subscript “reduced” refer to the reduced values used in the analysis.

The incremental multiplier ΣMsf is used to specify the increment of the strength reduction of the first calculation step and the final ΣMsf value is the stability factor at failure. This method resembles the calculation of stability factor as conventionally adopted in slip circle analysis because it is the ratio between the available strength and the strength at failure.

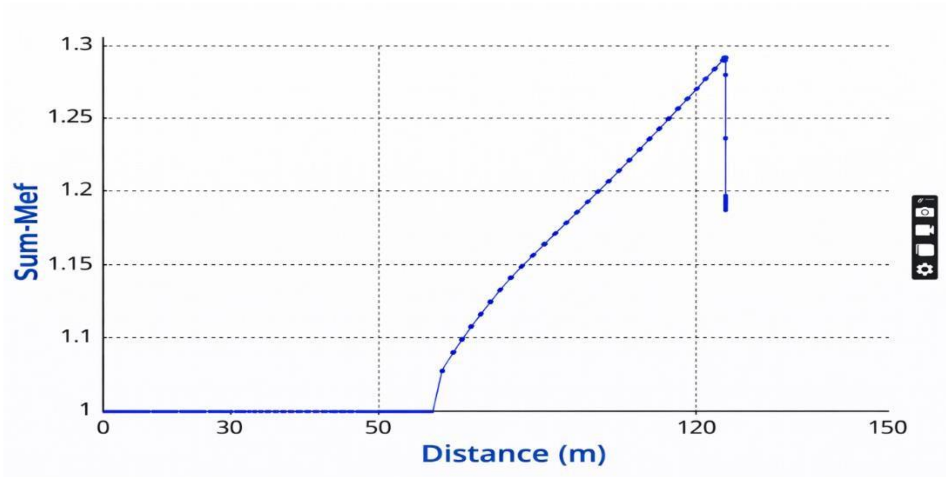


Figure 4-13: Plot of FoS during steady state of construction condition fully supply level

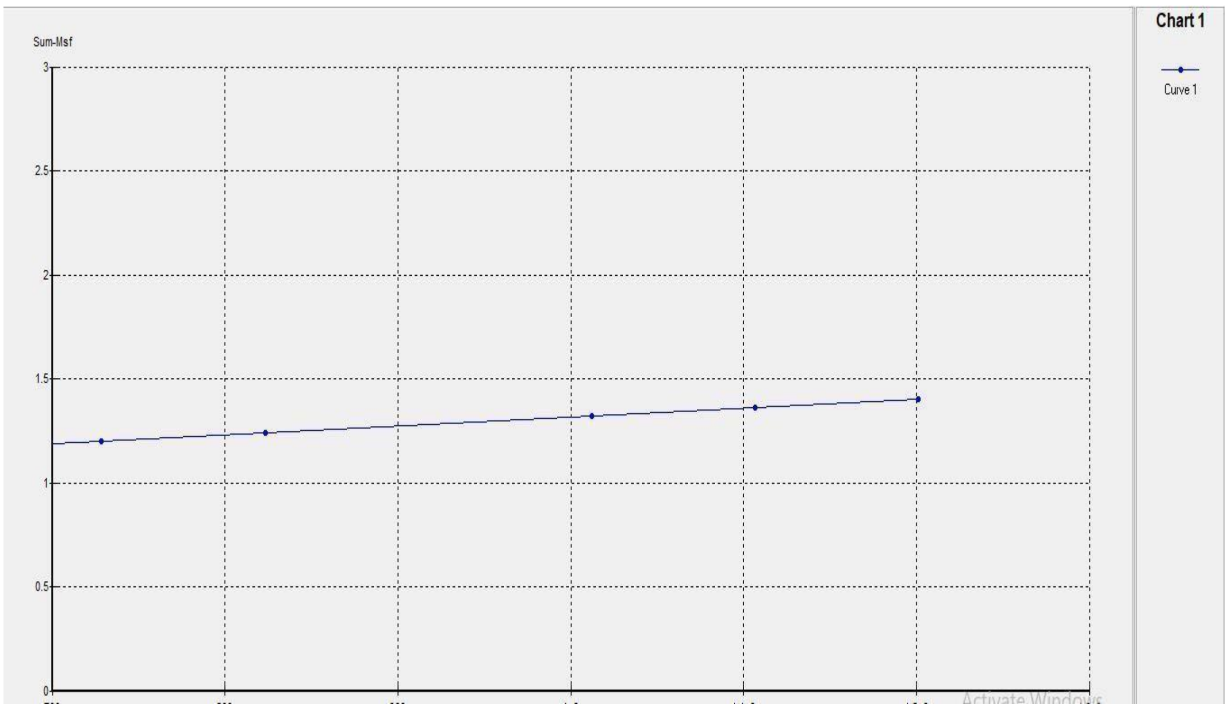


Figure 4-14: Plot of FoS during steady state of construction condition

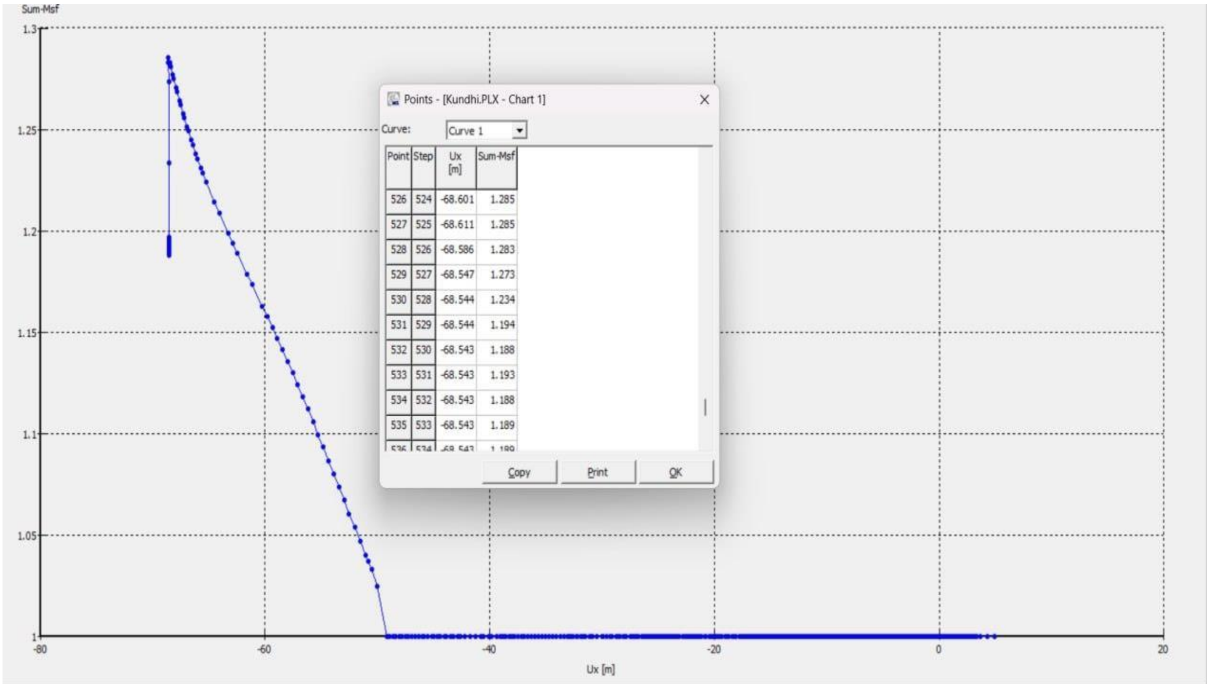


Figure 4-15: Plot of FoS during end of construction condition

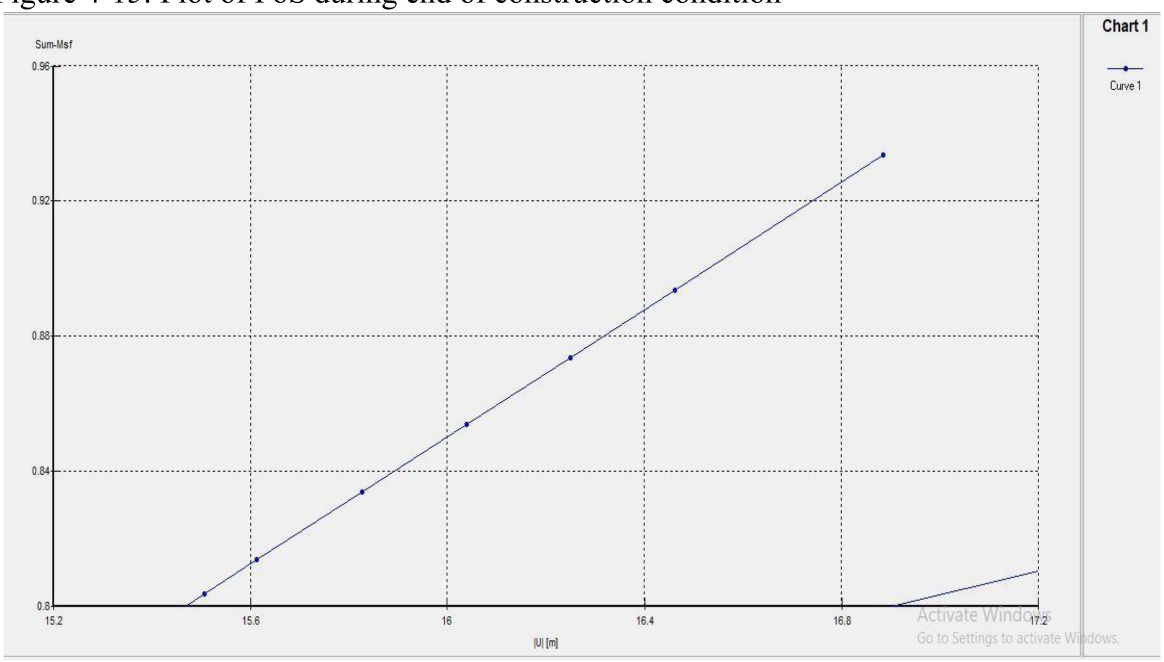


Figure 4-16: Plot of FoS during RDD condition

Required Minimum Factor of Safety

Table 4-1: Recommended factor of safety under different loading conditions

S.№	Load conditions	Critical slope	Minimum Factor of Safety (FS min)
1	Steady state condition	Down stream	1.5
		Up stream	1.5
2	Steady state with earth quake	Down stream	1.1
3	Sudden draw down	Up stream	1.3
4	End of construction	Down stream	1.3
		Up stream	1.3

Table 4-2: Results of PLAXIS 2D analyses of dam stability

S.№	Load conditions	Critical slope	Minimum Factor of Safety (FS min)	result in Geo-studio	States	results in plaxis	states
1	Steady state condition	Down stream	1.5	1.945	Safe	1.28	fail
		Up stream	1.5	2.438	safe	1.28	fail
2	Sudden draw down	Up stream	1.3	1.49	safe	0.94	fail
3	End of construction	Down stream	1.3	1.291	Fail	1.28	fail
		Up stream	1.3	2.227	safe	1.28	fail

4.3. Static Stress-Deformation Analysis

4.3.1. Static Stress

The maximum compressive forces are found on planes perpendicular to the face of the dam, either at the heel (primarily when the reservoir is empty) or at the toe (when the reservoir is full). The heel will experience the most compressive force when the reservoir is empty.

The proposed dam site is characterized by unconsolidated soil deposit underlain by sound bed rock unit. The unconsolidated organic soil overburden deposit is Alluvium. The deposit is characterized by Organic soil materials. The underlying sound bed rock unit is characterized by fresh to slightly weathered and fractured basalt and, laminated and bedded limestone rock.

The maximum stress developed by the dam and reservoir water on dam foundation is 0.93513 KN/m2 from PLAXIS analysis at full reservoir level, but from the design report the estimated bearing capacity of such rock mass is about 150Mpa (BS 8004 1986) that the bearing capacity of the foundation is greater than the maximum stress that kata dibe materials have got very bad 4.3engineering property that can cause adverse problem to the intended dam structure and, this implies that the foundation is safe against total vertical stresses.

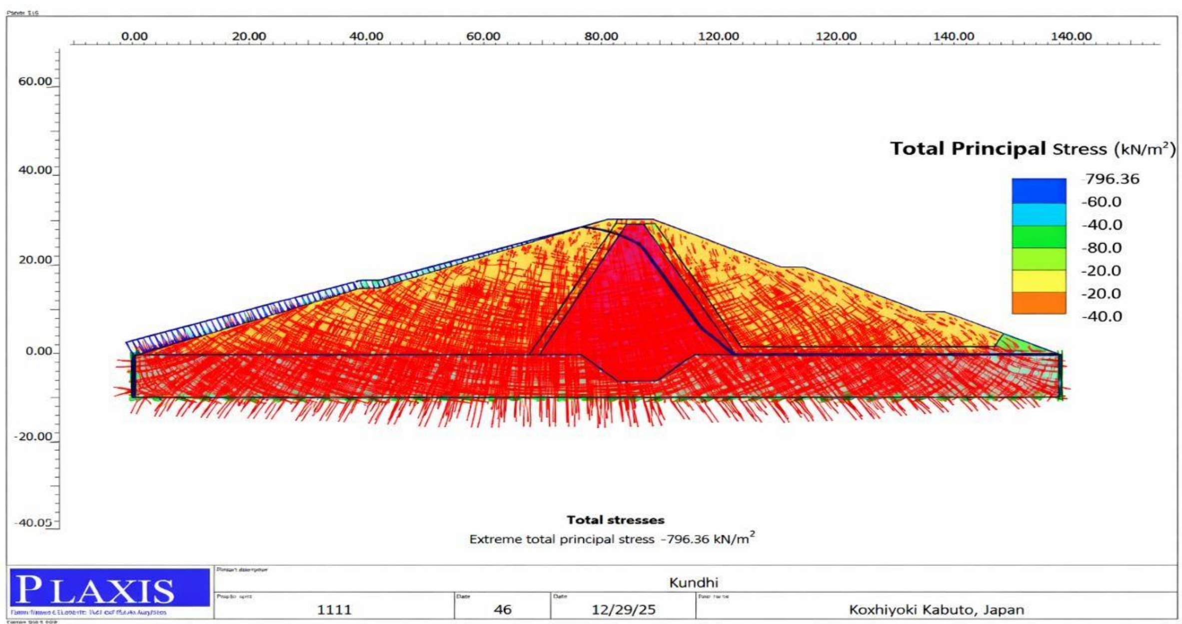


Figure 4-17: Maximum stress at normal water level

The distribution of total stresses within the Finna Kundhi embankment dam, obtained from PLAXIS finite element analysis. The colored contours represent the magnitude of total principal stress**,** while the arrows illustrate the direction and intensity of stress vectors within the embankment and foundation. The highest stresses are concentrated near the dam core and foundation contact, indicating zones where the self-weight of the embankment and overburden pressure are greatest. Stress magnitudes decrease toward the upstream and downstream slopes, which is consistent with expected embankment behavior.

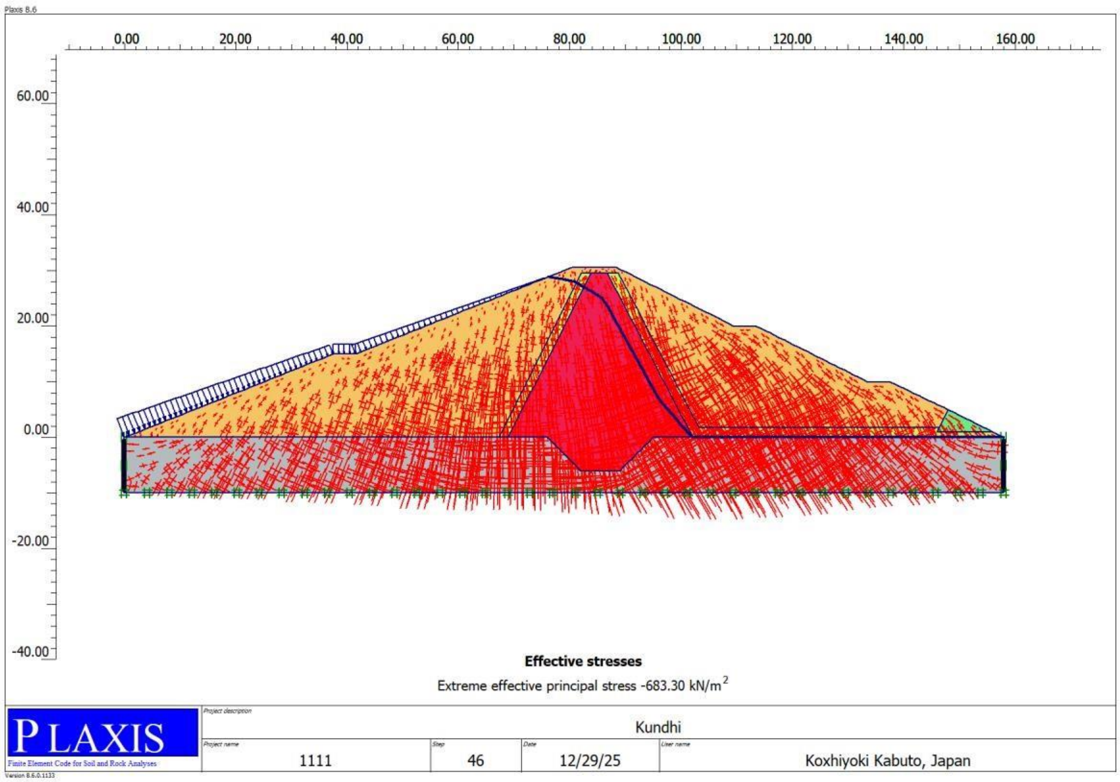


Figure 4-18: Effective stresses

The effective stress distribution, which governs soil shear strength and stability. The results indicate that effective stresses remain positive throughout the dam body, confirming the absence of uplift or instability conditions.

This confirms consistency between seepage, pore pressure, and stability analyses conducted using PLAXIS.

4.4. Comparison of Geo-studio Vs Plaxis

4.4.1. Seepage Analysis

GeoStudio (SEEP/W): Uses finite element seepage modeling with good steady-state and transient capabilities. Simple to use, suitable for preliminary and routine seepage assessment.

PLAXIS: Employs fully coupled hydro-mechanical finite element modeling. Better for anisotropic soils, transient seepage, and complex boundary conditions.

Verdict: PLAXIS is more robust for complex, coupled, or dynamic seepage problems.

4-3: Comparison of Seepage Analysis Results Using GeoStudio and PLAXIS

Parameter	**GeoStudio (SEEP/W)**	**PLAXIS V8.6**	**Interpretation**
Phreatic surface position	Controlled within drainage zone	Similar controlled position	Both models confirm effective seepage control
Maximum pore water pressure (kPa)	Slightly higher	Slightly lower	Difference due to numerical formulation
Seepage discharge ($m^3/s/m$)	Comparable	Comparable	Results show good agreement
Exit hydraulic gradient	Below critical	Below critical	No piping risk predicted

4.4.2. Slope Stability Analysis

GeoStudio (SLOPE/W): Uses limit equilibrium methods (e.g., Morgenstern-Price) for factor of safety calculation. Fast and conservative, ideal for homogeneous slopes.

PLAXIS: Uses finite element strength reduction (SSR) and captures stress-strain behavior, progressive failure, and deformation.

Verdict: PLAXIS is more realistic and robust for heterogeneous soils, seismic loading, and detailed failure analysis.

Table 4-4: Comparison of Slope Stability Results Using GeoStudio and PLAXIS

Loading condition	**GeoStudio FoS**	**PLAXIS FoS**	**Governing observation**
End of construction	Higher FoS	Lower FoS	FEM accounts for stress redistribution
Steady-state seepage	FoS > 1.5	FoS > 1.5	Dam stable under normal operation
Rapid drawdown	Marginally higher	Slightly lower	Critical condition for upstream slope

Strengths and Limitations

GeoStudio

Strengths: User-friendly, fast computation, integrated modules, good for preliminary design.

Limitations: Limited coupling, simplified stress-strain behavior, less suitable for complex geometries.

PLAXIS

Strengths: Advanced FEM, fully coupled analyses, realistic failure prediction.

Limitations: Steep learning curve, longer computation time, higher software cost.

Table 4-5: Robustness judgment

Analysis Type	More Robust Software	Reason
Seepage Analysis	PLAXIS	Better handles coupled flow-stress, anisotropy, and transient conditions.
Slope Stability	PLAXIS	Captures progressive failure, stress redistribution, and realistic deformation.
Overall, for Complex Dams	PLAXIS	Superior in modeling real-world complexity, heterogeneity, and dynamic loads.
Overall, for Routine Use	GeoStudio	Faster, simpler, and sufficiently accurate for standard projects.

5. CONCLUSIONS

This study conducted a Comparison of seepage and slope stability behavior of the Finna Kundhi earthen dam using GeoStudio (SEEP/W and SLOPE/W) and PLAXIS V 8.6 based on actual dam geometry, material properties, and operating reservoir conditions. The conclusions are derived from numerical analysis results obtained under steady-state seepage, end-ofconstruction, and rapid drawdown loading conditions.

Seepage analysis results from both software tools showed comparable flow patterns and phreatic surface locations. In all analyzed cases, the phreatic line remained confined within the dam body and safely discharged through the drainage system without intersecting the downstream slope. Computed seepage quantities and hydraulic gradients were within acceptable limits, indicating no potential risk of piping or internal erosion. PLAXIS generally predicted slightly higher pore water pressures than GeoStudio, particularly near the core and foundation interface, due to its coupled hydro-mechanical finite element formulation.

Slope stability analyses demonstrated that the dam satisfies recommended safety criteria under all considered loading conditions. GeoStudio produced marginally higher factors of safety compared to PLAXIS, reflecting the conservative nature of the limit equilibrium method. The minimum factors of safety were observed under rapid drawdown conditions on the upstream slope; however, all values remained above internationally accepted minimum requirements. Stress–deformation analysis using PLAXIS indicated no excessive deformation or progressive failure within the embankment.

Overall, the Finna Kundhi earthen dam is stable and safe under the analyzed conditions. The study confirms that GeoStudio is well suited for routine seepage and slope stability evaluation, while PLAXIS provides enhanced insight into stress–deformation and pore pressure interaction. The combined use of both software tools offers a reliable and comprehensive approach for embankment dam safety assessment under Ethiopian conditions.

6. RECOMMENDATIONS

Based on the comparative seepage and slope stability analyses of the Finna Kundhi embankment dam using GeoStudio and PLAXIS, the following recommendations are made for engineering practice and dam safety management.

Both GeoStudio and PLAXIS provided reliable results for seepage and slope stability analysis of the Finna Kundhi embankment dam. GeoStudio is recommended for routine design, preliminary assessment, and regulatory safety checks due to its simplicity and efficiency, while PLAXIS is suitable for advanced finite element–based analysis. A combined use of both tools is recommended for comprehensive dam safety evaluation.

Accurate geotechnical parameters are essential; therefore, detailed laboratory and field investigations are recommended to improve modeling reliability. Although seepage and stability results are within acceptable limits, regular inspection of seepage control measures and continuous monitoring using piezometers are necessary. Rapid drawdown is identified as the most critical condition; thus, controlled reservoir operation and periodic stability reassessment are recommended to ensure long-term dam safety.

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7. APPENDICES

7.1. Appendix Table

Appendix Table 7-1: Silent features of Kundhi dam and reservoir

Parameter	Value / Description
Project Name	Finna Kundhi Project
River Name	Kundhi
Geographic Headwork Location	
- Northing	N 536831
- Easting	E 367680, Zone 37N
- Riverbed Elevation	1594 m.a.s.l.
Administrative Headwork Site Location	
- Zone	Borena
- Woreda	Ele Waye Woreda
- Kebele	Elway Golba
Headwork Type	Zoned Embankment Dam
Dam Dimensions	
- Height	30.6 m
- Crest Length	705 m
- Crest Top Width	8 m
- Upstream Slope	1 Vertical: 2.5 Horizontal (1V:2.5H)
- Downstream Slope	1 Vertical: 2 Horizontal (1V:2H)
Catchment Area at Dam Site	210.26 km^2
Reservoir Characteristics	
- Reservoir Area at MWL	108.72 ha
- Full Reservoir Capacity at FRL	13.35 million m^3
Spillway Details	
- Type	Ogee Spillway
- Crest Width	8 m
Estimated Command Area	More than 842 ha

Appendix Table 7-2: Dam height determination

Parameter	Value (m.a.s.l)	Explanation
Normal Pool Level (NPL)	1611.0	Maximum reservoir water surface during normal operation
Lowest Riverbed Level	1594.0	Lowest elevation at dam axis cross-section
Height of Normal Pool above Riverbed	17.0	Calculated as NPL - Lowest riverbed level (1611 - 1594)
Alternative Height of Normal Pool	27.0	Given as 1109 - 1082 (likely from a different reference or section)
Spillway Flow Depth	1.50	Depth of flow over the spillway
Maximum Flood Level (MFL)	1110.5	Calculated as Normal Pool Level + Spillway flow depth (1109 + 1.5)
Freeboard and Settlement Allowance	To be added	Additional height above MFL for safety and settlement

Appendix Table 7-3: Major soil types in the catchment and their percentage

Soil Type/Group	Texture	SNAM/Class	Area (ha)	Area (%)
Haplic Xerosols	Clay-Loam	Xh15-3a-306	7600	100
Total			7600	100

Appendix Table 7-4: Foundation material engineering property

Foundation Geotech Parameters	Thickness	Hydraulic conductivity (K), cm/s	Cohesion (c) MPa	Internal Friction Angle	Bearing Capacity (MPa)	UCS,	Modules Of Defor mation(E)	PI	Unit Weight kN/m3
Layer 1- (Alluvial)	5	1x10-2- 10-4	0.01	33	0.4	0.025	-	10	15
Layer 2- (Residual)	0.75	5-Oct	0.0075	34	0.4	0.025	-	15	20
Layer 3- (weathered basalt)	≥ 0.75	NA	4.3	31.9	15.6	6.4	11927	NP	26

Appendix Table 7-5: Specification of Casagrande piezometer

PIEZOMETER SPECIFICATIONS	
Stand Pipe piezometer	
Porous tip	Slotted steel pipe with 50mm dia. covered with geotextile cloth. Length, see the drawing
Standpipe	Steel pipe 50 mm dia., with an inbuilt socket for jointing to gain the required length.
Length 'L' (m)	1 to 32m (refer the design drawing for detail)
Resolution	1 mm standard
Cable/Tape	High tensile virtually non-expandable, non-stretch, Polyethylene (PE) insulated flat steel tape
Tape/Cable Size	10 mm wide x 2 mm thick
Probe	Stainless steel with waterproof molding.
Power Supply	9 V, PP3 size battery operated complete with an onoff switch, buzzer (audio signal), LED (Visual signal) for power on and signal, flat cable connected to a probe, winding reel and carrying handle.
PIEZOMETER SPECIFICATIONS	
operating temperature range	(-20 to 80) ^{O}C
Pressure range	-100 to 3.5 Mpa, with an accuracy of ±0.5 percent
Bore diameter	100mm
Installation Location	Refer on the design drawing
Filter element technical specification	
Outer Diameter	37 mm
Filter wall thickness	5.0 mm
Maximum pore size	40 microns
Drive unit	Steel (GIS) driving tip and filter

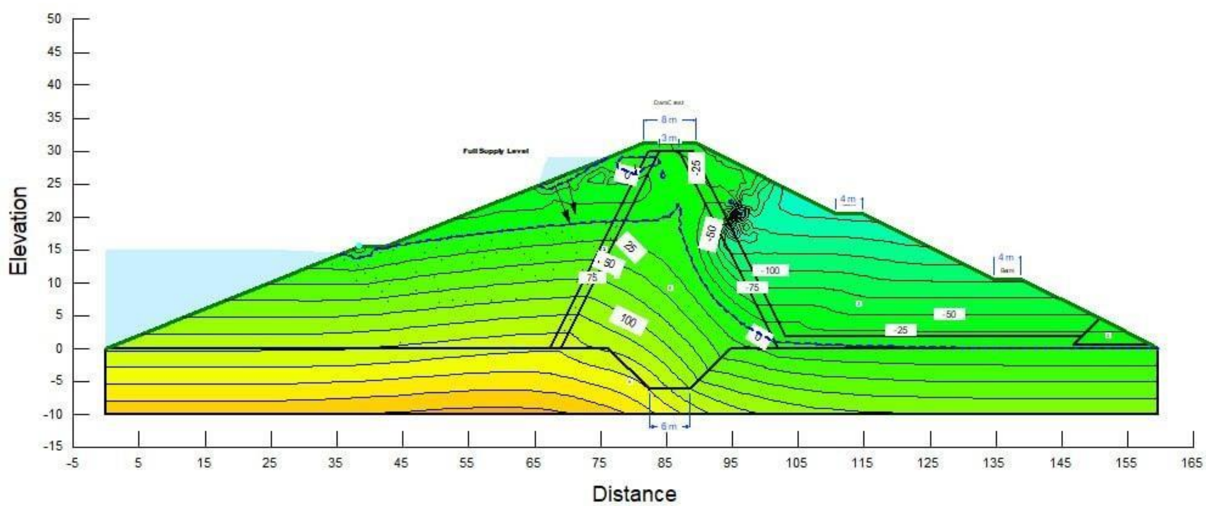
7.2. Appendix Figure

Appendix Figure 7-1: The dam store of water

Appendix Figure 7-2: Upstream of the dam

Appendix Figure 7-3: Upstream and downstream of the dam

Appendix Figure 7-4: Steady state condition



Appendix Figure 7-5: Phreatic surface, pore water pressure distribution, and seepage flow vectors under steady-state full supply level condition